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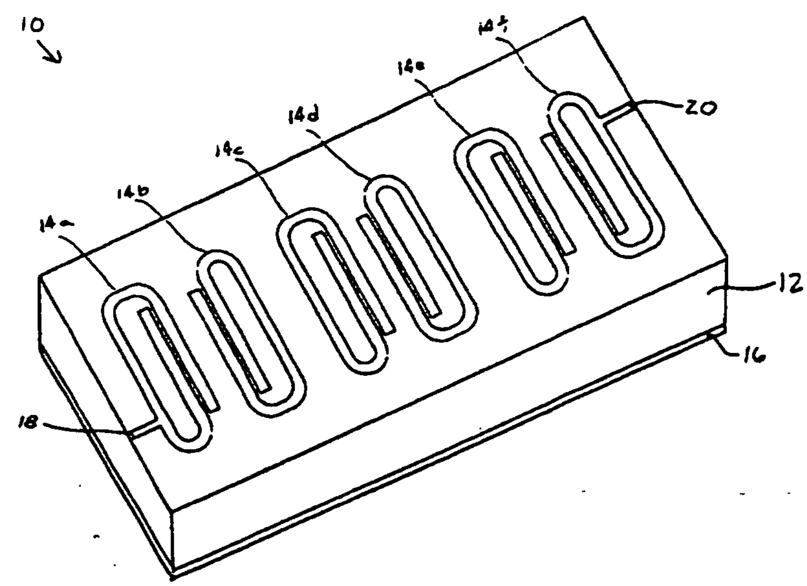

(57) Abstract

A planar filter (10) for performing signal filtering at radio frequencies is provided. The planar filter can include asymmetrical resonators (14a-14f), wherein each resonator is asymmetrical about a longitudinal center axis (23a-23f) through the resonator. In addition, the resonators can be grouped in coupled pairs (22a-22c) such that the resonators in each coupled pair are asymmetrical about a longitudinal center axis (32a-32c) between the paired resonators. In addition, a coupling structure (66, 68) is provided that includes both distributed coupling and tapped coupling to a resonator. Further, a bandstop filter device (70) is provided that includes coupling between resonators (72a-72d) in the filter.

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PLANAR RADIO FREQUENCY FILTER

FIELD OF THE INVENTION

The invention relates in general to radio frequency filter structures and, more particularly, to radio frequency filter structures having a planar configuration.

BACKGROUND OF THE INVENTION

A planar filter is a radio frequency filtration device having all of its circuitry residing within a relatively thin plane. To achieve this, planar filters are generally implemented using flat transmission line structures such as microstrip and stripline transmission lines. These transmission line structures normally include a relatively thin, flat conductor separated from a ground plane by a dielectric layer. Planar filters have been of interest in recent years because of their relatively small size, low cost and ease of manufacture.

Planar filters ca be comprised of one or more resonator elements. A resonator element is a transmission line configuration that is known to "resonate" at a certain center frequency. In general, a plurality of these resonator elements are arranged to achieve a desired filter response. For example, the resonators can be arranged so that only a predetermined range of frequencies (and harmonics of such) are allowed to pass through the filter from an input port to an output port. This type of filter is known as a "bandpass" filter and the predetermined range of frequencies is known as the pass band of the filter. In another arrangement, the resonators can be configured so that all frequencies are allowed to pass from an input port to an output port except for a predetermined range of frequencies (and harmonics of such). This type of filter is known as a "bandstop" filter and the predetermined range of frequencies is known as the stop band of the filter.

Planar filters, as well as the other filter types, have a number of important performance criteria. For example, it is generally desirable that a bandpass filter display very low insertion loss in the pass band of the

filter. Outside of the pass band, however, high rejection is desirable. Conversely, a bandstop filter requires relatively little loss outside of the stop band and a high amount of rejection within the stop band.

In many applications, both bandpass and bandstop filters require a relatively sharp cutoff at the band edges. That is, the transition from a low loss condition to a high loss condition should take place over a relatively narrow range of frequencies. Sharp cutoff is required, for example, in applications where a relatively large number of frequency bands exist within a given frequency range, to separate out the individual bands. The sharpness of the filter response cutoff depends upon such things as, for example, the quality factor of the filter (i.e., the Q factor), the number and type of resonators that are being used in the filter, the materials used in the filter, and the arrangement of the resonators in the filter.

Some applications now require filter structures that are very small in size. For example, a mobile handset in a cellular or PCS communications system requires a filter for preselection of a predetermined operational frequency range. Because the size of these handsets is constantly being reduced, the area that can be dedicated to filter units is correspondingly being reduced. In addition, as increased functionality is being added to these handsets, the space available for filters is further reduced. Another application requiring small sized filters is monolithic microwave integrated circuits (MMICs). MMICs generally comprise full microwave subsystems, such as a multichannel microwave receiver, disposed within a single small package. As is apparent, large, bulky filters could not be used in such systems.

A third application requiring small sized filters is tower-mounted receiver front ends used in wireless base stations. The close proximity of the receiver front end to the antenna minimizes the noise figure of the microwave

signal receiving system. For this application, the filters must be located in a temperature-controlled enclosure to shield them from ambient weather conditions. By utilizing small sized planar filters, rather than conventional cavity filters, the cost of maintaining this enclosure, as well as potentially deleterious effects of wind loading are reduced.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a planar filter structure having a reduced size.

It is another object of the present invention is to provide a planar filter structure having a relatively high Q value.

It is yet another object of the present invention to provide a planar filter structure having relatively sharp cutoff at the band edges.

It is still another object of the present invention to provide all of the above advantages within a single filter unit that is relatively inexpensive to produce.

The present invention relates to structures for providing bandpass and/or bandreject filter responses in radio frequency systems. The structures provide desired filter responses while occupying a relatively small amount of real estate on an underlying substrate. In this regard, the filter structures of the present invention are valuable in applications having a limited amount of available space. In addition, the filter structures are relatively easy and inexpensive to manufacture. The inventive structures can be implemented in a variety of different transmission line types including, for example, microstrip transmission line, stripline transmission line, and suspended substrate transmission line.

In one aspect of the present invention, a planar filter is provided having a plurality of resonator elements. Lines are provided for coupling energy into and out of the filter. In accordance with the invention, at

least one of the input and output structures uses both distributed line coupling and tapped coupling to perform the desired coupling function. In a related aspect of the invention, the coupling type used at the input of the filter is different from that used at the output of the filter. That is, for example, distributed coupling is used at the input while tapped coupling is used at the output. Alternatively, one of the input or the output can include both distributed and tapped coupling while the other includes just one type of coupling.

In another aspect of the present invention, a planar bandpass filter is provided that includes a plurality of resonating elements arranged in an approximately linear fashion. Each pair of adjacent resonating elements includes a longitudinal center axis therebetween. An odd number of the pairs include elements that are asymmetrical about the corresponding longitudinal center axis. It has been discovered that utilizing an odd number of asymmetrical pairs improves the rejection characteristics of the filter for a given number of resonating elements. In one embodiment, the resonators include novel "paper clip" resonators having a plurality of substantially parallel legs that are interconnected by folds.

In another aspect of the present invention, a planar bandstop filter is provided that comprises a plurality of resonating elements, wherein at least two of the resonating elements are directly coupled to one another. In one embodiment, a first side of a first resonator is coupled to a second resonator and a second side of the first resonator is coupled to a third resonator. The coupling to the second resonator is stronger than the coupling to the third resonator.

In another aspect of the present invention, a planar bandstop filter is provided that includes a plurality of resonating elements coupled to a through line, wherein a first of the resonating elements is directly coupled to a second of the resonating elements. The through line

connects the input of the filter to the output of the filter. The coupling between the first and second resonating elements is adapted to improve the rejection characteristics of the filter. In one embodiment of the invention, anisotropic coupling between resonators is achieved by utilizing resonators having a distributed capacitance between opposite ends of a conductor. To achieve a decreased amount of coupling between a first resonator and a second resonator, for a given distance between the resonators, a side of the first resonator that includes the distributed capacitance faces the second resonator. To achieve reduced coupling between a first and a third resonator, a meandering line is introduced into the side of the first resonator that faces the third resonator. The meandering line increases the effective distance between the first resonator and the second resonator (and hence decrease the coupling) while the actual distance between the resonators remains the same.

In yet another aspect of the present invention, a planar filter is provided that includes a resonator having a first, second, and third leg that are all substantially parallel to one another. The third leg is located between outer edges of the first and second leg. The first and second leg are connected by a first fold while the second and third legs are connected by a second fold. The "fold" can include, for example, a bend in the transmission line conductor. The resonator is asymmetrical about a first longitudinal center axis. The third leg can be spaced from the first leg so as to create a distributed capacitance between the legs. This distributed capacitance allows the overall dimensions of the resonator to be reduced. The resonator can also include a fourth leg that is spaced from the second leg to create a distributed capacitance therewith.

In still another aspect of the present invention, a planar filter is provided that includes a first resonator element and a second resonator element. The first

resonator element includes a first conductor with a first portion at a first end and a second portion at a second end. The conductor has a bend so that the first portion is opposite the second portion over at least a fraction of its length. The second element includes a third portion that is located between the first portion and the second portion of the first resonator element. In one embodiment, a dual element hairpin resonator is provided that includes two hairpin shaped resonators having their fingers interdigitally arranged.

In all aspects of the present invention, the resonators and other structures can be made out of superconducting materials to increase the Q value of the filters and reduce radiation from the resonators.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1a is an isometric view of a six pole bandpass filter in accordance with the present invention;

Fig. 1b is a top view of the metallization pattern for the filter of Fig. 1a illustrating a plurality of three leg "paper clip" resonators;

Fig. 2a is a computer simulated graph showing a predicted response of the filter of Figs. 1a and 1b;

Figs. 2b is a graph illustrating a measured response (uncalibrated) of the filter of Figs. 1a and 1b showing the lack of even-ordered harmonics in the filter response;

Fig. 3 is a top view of the metallization pattern of a four leg "paper clip" resonator in accordance with the present invention;

Fig. 4 is a top view of the metallization pattern of a resonator having an interdigital coupling structure in accordance with the present invention;

Fig. 5 is a top view of the metallization pattern of a five pole filter having two coupled resonator pairs and a single symmetric resonator in accordance with the present invention;

Fig. 6 is a top view of the metallization pattern of an eight pole band pass filter using "pinched end" resonators and having tapped input and output lines in accordance with the present invention;

Fig. 7 is a top view of the metallization pattern of a six pole bandpass filter using "pinched end" resonators and having input and output lines utilizing distributed coupling in accordance with the present invention;

Fig. 8 is a top view of the metallization pattern of an eight pole bandpass filter using "pinched end" resonators and having input and output lines utilizing both tapped and distributed coupling in accordance with the present invention; and

Fig. 9 is a top view of the metallization pattern of a four pole bandstop filter utilizing coupled "pinched end" resonators in accordance with the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The present invention relates to structures for providing bandpass and/or bandreject filter responses in radio frequency systems. The structures provide desired filter responses while occupying a relatively small amount of real estate on an underlying substrate. In this regard, the filter structures of the present invention are valuable in applications having a limited amount of available space. In addition, the filter structures are relatively easy and inexpensive to manufacture. The inventive structures can be implemented in a variety of different transmission line types including, for example, microstrip transmission line, stripline transmission line, and suspended substrate transmission line. It should be appreciated that the term "radio frequency", as used herein, is meant to apply to all portions of the electromagnetic spectrum that are capable of propagation on the transmission structures disclosed herein, including, for example, high frequency (HF), very high frequency (VHF), microwaves, millimeter waves, and submillimeterwaves.

Fig. 1a illustrates a six pole microstrip bandpass filter 10 in accordance with one embodiment of the present invention. The bandpass filter of Fig. 1a was originally disclosed in provisional U.S. Patent Application Serial No. 60/020,863 entitled "ASYMMETRIC MICROWAVE RESONATING DEVICE" which is incorporated herein by reference. As illustrated, the filter 10 includes a planar substrate material 12, a ground plane 16 underlying the substrate 12, a plurality of resonator elements 14a-14f, an input line 18, and an output line 20. In operation, an electromagnetic signal is delivered to input line 18 from an external source after which it is acted upon by the resonators 14a-14f. The resonators 14a-14f allow certain frequencies in the electromagnetic input signal to couple through from the input line 18 to the output line 20, while other frequencies are rejected (i.e., reflected back out through input line 18).

Fig. 1b is a top view of the metallization pattern deposited on the top surface of substrate 12 showing the general configuration of the resonators 14a-14f. The resonators 14a-14f each include a single continuous transmission line conductor formed into a shape resembling that of a paper clip, and hence are called "paper clip" resonators. The paper clip resonators illustrated in Fig. 1b each have three parallel legs that are connected by folds at the ends of the resonator. The electrical length of each resonator is approximately equal to one-half of a guide wavelength (i.e., $\lambda g/2$) at the center frequency of the resonator. As illustrated in Fig. 1b, each resonator 14a-14f includes a portion 24 wherein a first leg 26 at a first end of the conductor is spaced from a third leg 28 at a second end of the conductor by a relatively narrow gap 30. The dimensions of the gap 30 are chosen so that a desired distributed capacitance exists between the ends 26, 28 of the conductor. In a typical embodiment, the width of the gap 30 is between 0.1 and 10 mils. Because of the presence of an additional capacitance in the resonator, the

size of the resonator can be reduced while maintaining a desired resonating frequency.

The spacing between successive resonators is determined based upon a coupling required to achieve a desired filter response. If the resonators are placed too closely to one another, the resonators will be too tightly coupled, resulting in an undesired shift or spread in the resonance characteristic of the filter.

As illustrated in Fig. 1b, the resonators 14a-14f are each asymmetrical about a corresponding longitudinal center axis 23a-23f. The longitudinal center axes 23a-23f are substantially perpendicular to the direction 29 of energy flow through the filter. In addition to the elemental asymmetry, the resonators 14a-14f are also arranged into coupled pairs 22a-22c that are each asymmetrically arranged about a corresponding central axis 32a-32c extending longitudinally between the resonators. Because the arrangement between each pair 22a-22c is asymmetrical, the coupling between the resonators within each pair is reduced, thereby allowing the resonators within each pair to be spaced more closely together. This decreased spacing between the resonators in each pair reduces the overall dimensions of the filter 10. In conceiving of the present invention, it has been determined that an optimal filter response is achieved when the number of "flips" within the chain of resonators is odd. A "flip" is defined as a double rotation of a resonator about two axes of rotation. For example, the positioning of resonator 14b in Fig. 1b can be obtained by rotating resonator 14a once about longitudinal center axis 32a and once about latitudinal axis 34. The positioning of resonator 14c can be obtained by a similar double rotation of resonator 14b and so on. In accordance with the present invention, the latitudinal axis 34 does not have to be centered on the element. As described above, in a preferred embodiment of the present invention, the number of flips is odd. It has been discovered that use of an odd number of flips and a

tapped input and/or output produces zeros in the transfer function of the filter that occur at the band edges of the filter response resulting in sharper cutoffs at the band edges than are normally obtainable.

Input 18 and output 20 are each located on either side of and substantially equidistant from the latitudinal center axis 34. As illustrated, the input 18 and the output 20 each comprise a conductively coupled tap on a corresponding resonator element 14a, 14f. The position of the tap on the resonator depends on the desired freqency, bandwidth, ripple, filter order, and the width of the resonator line.

The width of the conductor forming each resonator 14a-14f preferably produces a line impedance ranging from about 10 to about 80 ohms. As discussed above, the distance between the first leg 26 and the third leg 28 is typically from about 0.1 mil to about 10 mils. The distance between a second leg 27 and the third leg 28 is typically from about 1 to about 5 line widths. The distance 100 between adjacent resonators in a given pair typically ranges from about 1 to about 250 mils. The distance 102 between adjacent pairs typically ranges from about 2 to about 400 mils.

The various components of the filter of Figs. 1a and 1b can have a variety of compositions in accordance with the present invention. The resonator conductors and ground plane can be composed of a variety of conducting and superconducting materials, including (a) nonsuperconducting metals, such as gold, copper, and silver, and (b) high temperature superconductors, such as ytrium barium copper oxide (YCBO) and thallium barium calcium copper oxide (TBCCO). Use of superconducting materials is advantageous because they reduce metallization losses in the filters, thus enabling higher Q values to be observed in the filters. This means the filters have lower insertion loss in the passband and sharper out-of-band attenuation. The dielectric substrate can be composed of any dielectric

material, such as air, alumina, quartz, sapphire, lanthanum aluminate (LAO), magnesium oxide (MgO), teflon (PTFE), teflon based board materials such as "Duroid" sold by Rogers Corporation, gallium arsenide (GaAs), and other common circuit board materials such as FR4/G10.

Fig. 2a is a computer simulated response characteristic for the filter illustrated in Figs. 1a and 1b. As shown, the simulated filter response has a very low loss 42 in the passband and very sharp cutoffs 40a, 40b at the edges of the passband. In addition, the response is relatively symmetric about a center frequency. The sharp cutoffs 40a, 40b are the result of zeros in the transfer function of the filter that are created due to tapping and having an odd number of "flips" between the resonators. The zeros are evident in the simulated response as the depressions 44a and 44b in the skirt of the graph of Fig. 2a.

Fig. 2b is a graph showing the measured response of the filter (uncalibrated) over a large frequency range. As shown, rejection is very high at the even ordered harmonics (i.e., >70 dB). In addition, parasitics are substantially suppressed in the vicinity of the passband. In addition, calibrated measurements of insertion loss in the passband indicate that the loss is below 0.3 dB.

The design principles used to reduce circuit dimensions in the filter of Figs. 1a and 1b are not limited to the use of the "paper clip" resonator structure disclosed therein. In fact, any resonator design that is asymmetrical about a longitudinal center axis through the element can be used in accordance with the present invention. For example, the element 46 of Fig. 3 can be used in the filter of Figs. 1a and 1b. Resonator 46 is similar to the "paper clip" resonators 14a-14f of Figs. 1a and 1b, but includes a fourth leg 48 that provides further distributed capacitance in the resonator 46. This additional distributed capacitance allows the overall

dimensions of resonator 46 to be further reduced while still achieving a desired resonant frequency.

Fig. 4 illustrates another resonator design that can be used in the filter of Figs. 1a and 1b. Resonator 50 is asymmetrical about a longitudinal center axis 52 passing through the resonator. On one side of the resonator 50, an interdigital coupling structure 54 is provided for creating the required distributed capacitance. It should be appreciated that the resonator embodiment illustrated in Fig. 4 can include any number of interdigital fingers in coupling structure 54 and is not limited to the illustrated number (i.e., 3).

Fig. 5 is the top view of the metallization pattern for a five pole bandpass filter in accordance with the present invention. As illustrated, the filter of Fig. 5 includes two pair 36a, 36b of asymmetrical resonator elements on either side of a single symmetrical resonator element 38 having a "hairpin" shape. By using a symmetrical resonator element 38 in conjunction with the asymmetrical coupled pairs 36a, 36b, a bandpass filter having an odd number of poles is achievable. In fact, any combination of symmetrical resonator elements and asymmetrical pairs is possible in accordance with the present invention.

Fig. 6 illustrates the metallization pattern for an eight pole filter in accordance with the present invention. The filter of Fig. 6 utilizes "pinched end" resonators 106a-106h that are each symmetrical about a corresponding longitudinal center axis 108. Each "pinched end" resonator 106a-106h includes a central portion 110 wherein a first end portion 112 of a conductor is spaced from a second end portion 114 of the conductor to form a distributed capacitance therebetween. As discussed previously, this distributed capacitance results in smaller resonators 106a-106h for a given resonant frequency. When constructed from superconducting materials, the "pinched end" resonators display high-Q values with very little radiation loss,

despite the fact that each resonator has six 90 degree bends. It is believed that the high conductivity of the superconducting material insures that fields are "contained" within the dielectric substrate material, which minimizes radiation at the bends. Similarly, the distributed capacitance between the first end portion 112 and the second end portion 114 of the conductor further contains the fields and reduces radiation.

As shown, each successive resonator in the filter is "flipped" with respect to the previous resonator and the total number of "flips" is odd. The filter of Fig. 6 includes tapped input and output lines 58, 60 similar to those in the filter of Figs. 1a and 1b. One important benefit of using tapped input/output lines is improved near out band rejection by introducing attenuation zeros.

Fig. 7 illustrates a six pole bandpass filter having "pinched end" resonators that utilize input and output lines 62, 64 that are coupled to an input resonator 116 and an output resonator 18, respectively, using distributed coupling. One important benefit of using distributed coupling in the input and/or output is the ability to optimaize the return loss by perturbing the input/output couplings to the resonator. In conceiving of the present invention, it was determined that enhanced performance could be achieved by combining tapped coupling and distributed coupling in the input and/or output structures. That is, dual coupling arrangements provide benefits associated with both coupling methods. Fig. 8 illustrates an eight pole bandpass filter that includes both distributed and tapped coupling on both an input 66 and an output 68. It should be appreciated that, in accordance with the present invention, the type of coupling used at the input of a filter can be different from the type used at the output of the filter. For example, the input may use distributed coupling, while the output uses tapped coupling. Also, the input can use a dual coupling arrangement, while the output uses a single coupling type.

Fig. 9 illustrates a four pole bandstop filter 70 in accordance with the present invention. The filter 70 includes four "pinched end" resonators 72a-72d each coupled to a meandering through line 78. The filter 70 als o includes an input port 74 and an output port 76 for coupling energy into and out of the meandering through line 78. During operation, a radio frequency signal is applied to the input port 74 of the filter from an exterior source and begins to propagate along the meandering through line 78. As the radio frequency signal passes one of the resonators, undesired frequency components in the signal are drawn out of the signal by the resonating action of the resonator.

By utilizing multiple identical resonators, the filter 70 can achieve a bandpass characteristic having relatively sharp cutoffs at the band edges. In addition, in conceiving of the present invention, it was determined that further sharpening of the cutoffs could be achieved by introducing coupling between the resonators of the filter. For example, in the filter 70 of Fig. 9, each resonator is directly coupled to an opposing resonator. That is, resonator 72a is directly coupled to resonator 72c, and resonator 72b is directly coupled to resonator 72d. By introducing this coupling between opposing elements, additional zeros are formed in the transfer function of the filter 70 at the edges of the stopband.

To form the required zeros in the transfer function, it is important that coupling between the aforementioned pairs be optimized while coupling between other pairs, such as between resonator 72a and resonator 72b, or between resonator 72c and resonator 72d, be minimized. In conceiving of the present invention, it was appreciated that anisotropic coupling characteristics could be achieved by properly choosing the type and arrangement of the elements. For example, it was found that decreased coupling could be achieved between a first and a second pinched end resonator by arranging the resonators so that

the side having the pinched end on the first resonator faces the same side on the second resonator. For example, with reference to Fig. 9, side 80a of resonator 72a faces side 80c of resonator 72c and side 80b of resonator 72b faces side 80d of resonator 72d.

In addition to the above, it was appreciated that coupling could be reduced between two resonators by using a meandering line on each of the coupled sides between the resonators. For example, with reference to Fig. 9, resonators 72a and 72b both include meandering lines 82a and 82b, respectively, on the sides facing one another. The same applies to resonators 72c and 72d. By using a meandering line, the effective distance between the elements is increased, thereby decreasing coupling between the elements, while the actual distance between the elements remains the same. In this way, the overall dimensions of the filter 70 can be reduced while still achieving a desired low coupling between certain elements.

To achieve a desired filter response, a predetermined electrical distance must be provided on through line 78 between the coupling points of the four resonators 72a-72d. To reduce the overall dimensions of the filter 70, a meandering through line 78 has been implemented. By having the through line 78 follow a winding path, rather than a straight one, the elements 72a-72d can be spaced closer together while still maintaining the desired electrical length between coupling points. This reduces the size of the filter.

By introducing coupling between the resonator elements, a quasi-elliptic filter response is achieved rather than a Chebyshev or Butterworth filter response. Because a quasi-elliptic filter response, having very sharp cutoffs, is achieved, the number of resonators required for sharp stopband cutoff characteristics is reduced. Reducing the number of resonators naturally reduces the size of the filter.

It should be appreciated that the metallization structures disclosed herein can be produced on a substrate by well known deposition and masking techniques. In addition, sheet metal stamping and other processes can be used to create slab line or other airloaded transmission structures.

Although the present invention has been described in conjunction with its preferred embodiments, it is to be understood that modifications and variations may be resorted to without departing from the spirit and scope of the invention as those skilled in the art readily understand. For example, the techniques and structures described above are not limited to use with half-wavelength resonators and can also be used with other resonator types, such as quarter-wavelength resonators. Such modifications and variations are considered to be within the purview and scope of the invention and the appended claims.

What is claimed is:

1. A planar filter for radio frequency energy, comprising:

a plurality of resonating elements separated from a ground structure by a dielectric layer, the plurality of resonating elements including input and output resonating elements; and

an input for radio frequency energy in communication with the input resonating element and an output for the radio frequency energy in communication with the output resonating element, wherein at least one of the input and output has a first portion spaced from a corresponding one of the input and output resonating elements for distributively coupling a first component of the radio frequency energy between the first portion and the corresponding one of the input and output resonating elements and a second portion physically connected to the corresponding one of the input and output resonating elements for tap coupling a second component of the radio frequency energy between the second portion and the corresponding one of the input and output resonating elements such that the first component of the radio frequency energy substantially excludes the second component of the radio frequency energy.

2. The planar filter of Claim 1, wherein:

said plurality of resonating elements are arranged in an approximately linear fashion and each pair of adjacent resonating elements has a corresponding longitudinal center axis located therebetween, the corresponding longitudinal center axis being substantially normal to a direction of flow of radio frequency energy through the filter, wherein a number of the pairs of adjacent resonating elements are asymmetrical to one another relative to the corresponding longitudinal center axis, and wherein the number of pairs of adjacent resonating elements that are asymmetrical to one another relative to the corresponding longitudinal center axis is odd.

3. A planar filter for radio frequency energy, comprising:

a plurality of resonating elements separated from a ground structure by a dielectric layer, said plurality of resonating elements including an input resonating element and an output resonating element;

an input for coupling radio frequency energy from an exterior environment to said input element; and

an output for coupling radio frequency energy from said output resonating element to said exterior environment;

wherein one of said input and said output includes a first conductive portion that is physically connected to a corresponding one of said input resonating element and said output resonating element for conductively transferring radio frequency energy therewith and the other of said input and said output includes a second conductive portion that is spaced from a corresponding one of said input resonating element and said output resonating element for radiatively transferring radio frequency energy therewith.

4. The planar filter of Claim 3, wherein:

said other of said input and said output also includes a third conductive portion that is physically connected to a corresponding one of said input resonating element and said output resonating element for conductively transferring radio frequency energy therewith.

5. A planar bandpass filter for radio frequency energy, comprising:

a plurality of resonating elements arranged in an approximately linear fashion, wherein each pair of adjacent resonating elements has a corresponding longitudinal center axis located therebetween, the corresponding longitudinal center axis being substantially normal to a direction of flow of radio frequency energy through the filter, wherein a number of the pairs of adjacent resonating elements are asymmetrical to one another relative to the corresponding longitudinal center axis, and wherein the number of pairs

of adjacent resonating elements in the plurality of resonating elements that are asymmetrical to one another relative to the corresponding longitudinal center axis is odd.

6. The planar filter of Claim 5, wherein at least one resonating element in the plurality of resonating elements has a plurality of legs and folds, wherein a first leg, a second leg, and a third leg are substantially parallel to one another, the first and second legs defining an outer boundary of the resonating element and the third leg being located between an outer edge of the first leg and an outer edge of the second leg, and wherein the first and second legs are connected by a first fold and the second and third legs by a second fold, the second fold being different from the first fold, and wherein the at least one resonating element is asymmetrical about a longitudinal center axis through the center of the resonating element that is substantially normal to a direction of flow of radio frequency energy through the filter.

7. The planar filter of Claim 5, wherein at least one resonating element in the plurality of resonating elements includes a superconducting material.

8. The planar filter of Claim 7, wherein:

said superconducting material is disposed in a continuous line having a third portion, a fourth portion, and a total length, wherein said third portion is spaced apart from and approximately parallel to said fourth portion to form a distributed capacitance between said third portion and said fourth portion.

9. The planar filter of Claim 8, wherein the length of said third portion that is adjacent to said fourth portion is approximatiely 10% of the total length.

10. The planar filter of Claim 8, wherein the distance between the third portion and the fourth portion of the line is approximately 5 mils.

11. The planar filter of Claim 8, wherein the distributed capacitance is approximately 2 picofarads.

12. The planar filter of Claim 8, wherein the planar filter has an unloaded Q of at least about 25,000.

13. A planar bandstop filter for radio frequency energy, comprising:

a plurality of resonating elements, wherein a distance between at least two of the resonating elements is sufficient to permit radio frequency energy to be transmitted by direct coupling between the at least two resonating elements when radio frequency energy is applied to the filter.

14. The planar bandstop filter of Claim 13, wherein a first side of a first resonating element directly couples to a second resonating element and a second side of the first resonating element directly couples to a third resonating element, the first and second sides being different from one another, such that the first side passes a first portion of the radio frequency energy to the second resonating element and the second side passes a second portion of the radio frequency energy to the third resonating element.

15. The planar bandstop filter of Claim 14, wherein the energy level of the first portion exceeds that of the second portion.

16. The planar bandstop filter of Claim 13, wherein at least one of the resonating elements is formed from a continuous line of a superconducting material and wherein a first length of the line is spaced apart from a second length of the line to form a capacitance therebetween.

17. The planar bandstop filter of Claim 13, wherein an interresonator coupling coefficient between the at least two resonating elements is dependent on a bandwidth of said filter.

18. A planar bandstop filter for radio frequency energy, comprising:

an input for receiving radio frequency energy from an exterior environment;

an output for delivering radio frequency energy to said exterior environment;

a through transmission line for transferring radio frequency energy from said input to said output; and

a plurality of resonating elements coupled to said through transmission line, wherein a first of the resonating elements is directly coupled to a second of the resonating elements.

19. The filter of Claim 18, wherein:

said first resonating element and said second resonating element are both directly coupled to said through transmission line.

20. The filter of Claim 18, wherein:

said direct coupling between the first and second resonating elements is adapted to improve rejection characteristics within a stopband of the filter.

21. The filter of Claim 18, wherein:

said first and second resonating elements have an interresonator coupling coefficient therebetween that is dependent on a bandwidth of said filter.

22. The filter of Claim 21, wherein:

said first resonating element includes a transmission line conductor having a first end and a second end, said transmission line conductor being arranged such that a portion of the transmission line conductor at said first end is located proximate to a portion of the transmission line conductor at said second end to create a distributed capacitance therebetween.

23. The filter of Claim 22, wherein:

said distributed capacitance is located on a first side of said first resonating element; and

said first side of said first resonating element provides a majority of the coupling with said second element.

24. The filter of Claim 22, wherein:

said distributed capacitance is located on a first side of said first resonating element; and

said first side of said first resonating element is facing said second element.

25. The filter of Claim 18, wherein:

said plurality of resonating elements includes a third resonating element, different from said first and second resonating elements, that is directly coupled to said first resonating element, wherein the coupling between said first and second resonating elements is stronger than the coupling between said first and third resonating elements.

26. The filter of Claim 25, wherein:

said first resonating element includes a second side, different from said first side, that provides a majority of the coupling with said third element; and

said second side of said first resonating element is meandered to reduce coupling with said third element.

27. The filter of Claim 18, wherein:

said through transmission line is meandered to reduce the overall dimensions of said filter.

28. A planar filter for radio frequency energy, comprising:

a first resonating element having a plurality of legs and folds, wherein a first leg, a second leg, and a third leg are substantially parallel to one another, the first and second legs defining an outer boundary of the first resonating element and the third leg being located between an outer edge of the first leg and an outer edge of the second leg, wherein the first and second legs are connected by a first fold and the second and third legs by a second fold, the second fold being different from the first fold, wherein the first resonating element is asymmetrical about

a first longitudinal center axis that is substantially parallel to said first, second and third legs.

29. The planar filter of Claim 28, wherein:

said second fold is located inside said first fold.

30. The planar filter of Claim 28, wherein:

said third leg is spaced from said first leg so as to create a distributed capacitance therebetween.

31. The planar filter of Claim 28, further comprising a second resonating element spaced from and coupled to the first resonating element and having the same shape as the first resonating element, wherein the first resonating element and the second resonating element are asymmetrical about a second longitudinal center axis located midway between an outer boundary of the first resonating element and an outer boundary of the second resonating element.

32. The planar filter of Claim 28, wherein the first and second folds are located at opposing ends of the first resonating element.

33. The planar filter of Claim 28, wherein the filter has a Chebyshev-type response.

34. The planar filter of Claim 28, further comprising an input and output to the filter, the resonating element having a latitudinal center axis that is substantially parallel to the direction of flow of radio frequency energy through the filter, the input and output being located on opposing sides of the latitudinal center axis.

35. The planar filter of Claim 28, further comprising:

a fourth leg, located between the first and second legs, that is connected to said third leg by a third fold.

36. The planar filter of Claim 35, wherein:

said fourth leg is substantially parallel to said first, second, and third leg.

37. The planar filter of Claim 35, wherein:

said fourth leg is spaced from said second leg so as to create a distributed capacitance therebetween.

38. The planar filter of Claim 28, wherein:

said first leg and said third leg are part of an interdigital coupling structure.

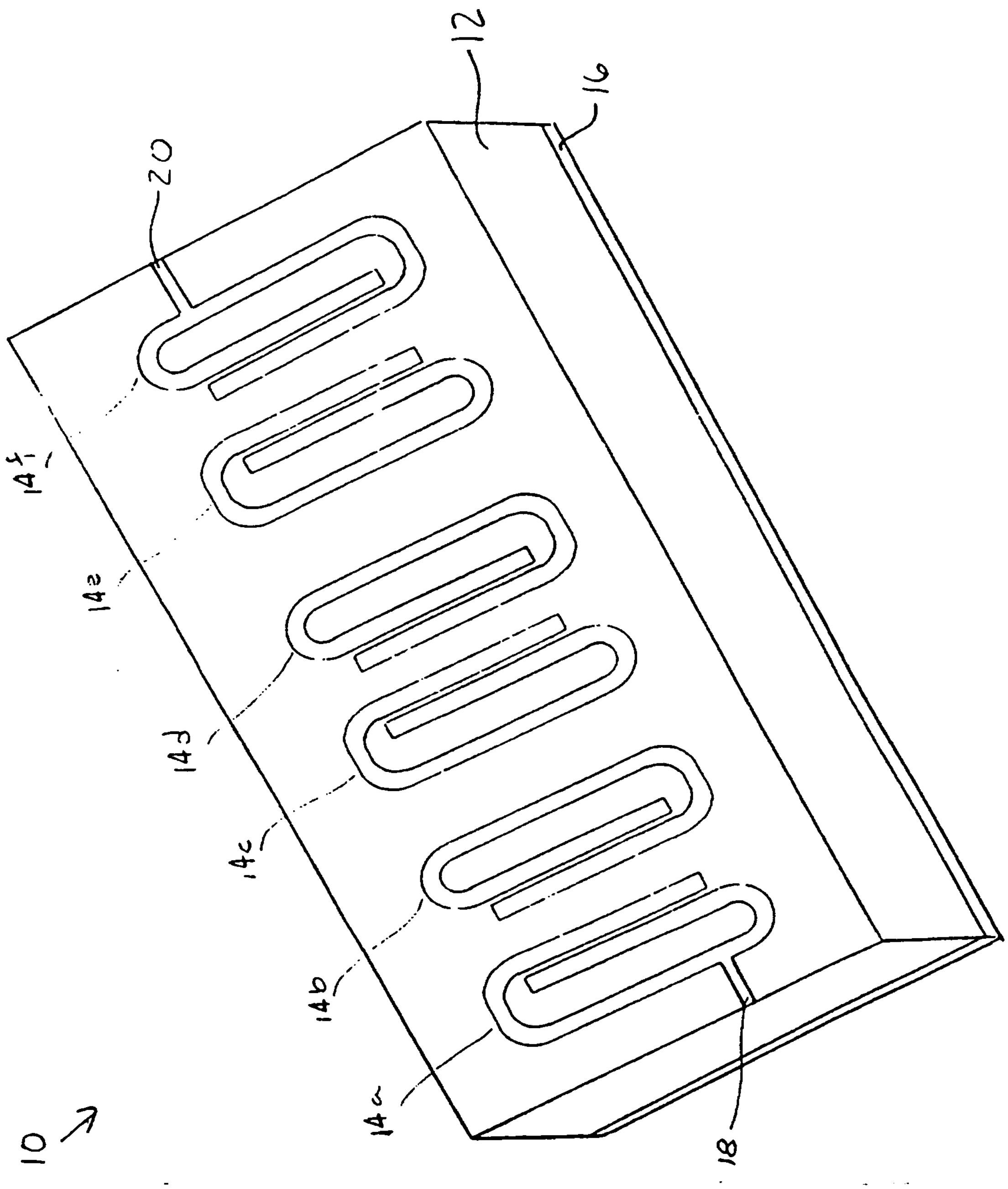
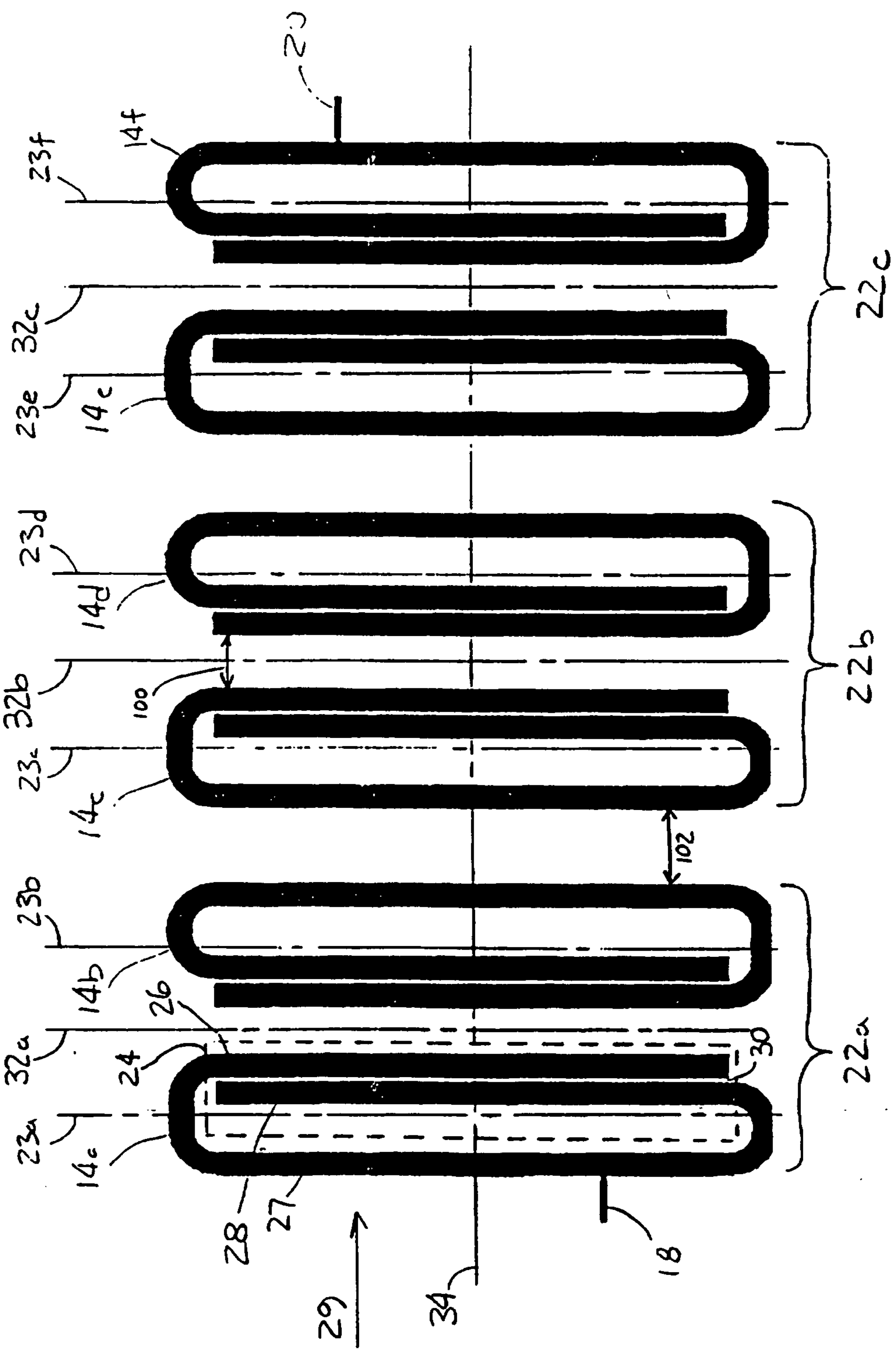


FIG. 1a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23e
14c
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14d
32b
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22b
23c
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22a
23a
14a
28
27
29
34
18

FIG. 1b

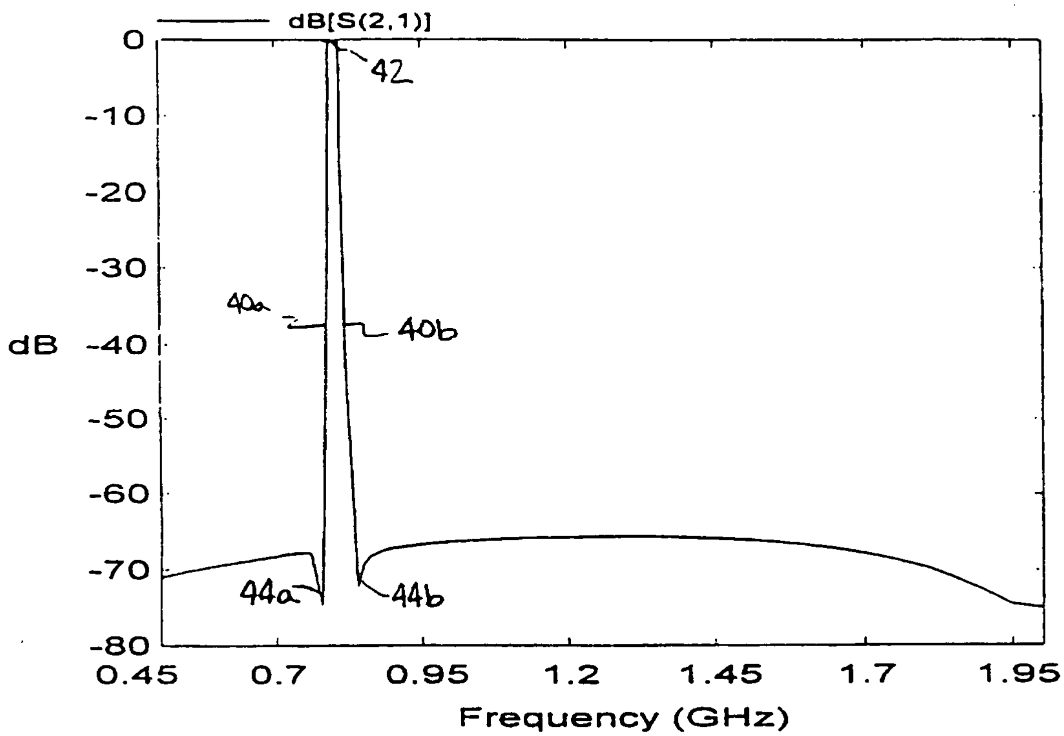

dB[S(2,1)]
0
-10
-20
-30
-40
-50
-60
-70
-80
dB
0.45
0.7
0.95
1.2
1.45
1.7
1.95
Frequency (GHz)
42
40a
40b
44a
44b

FIG. 2a

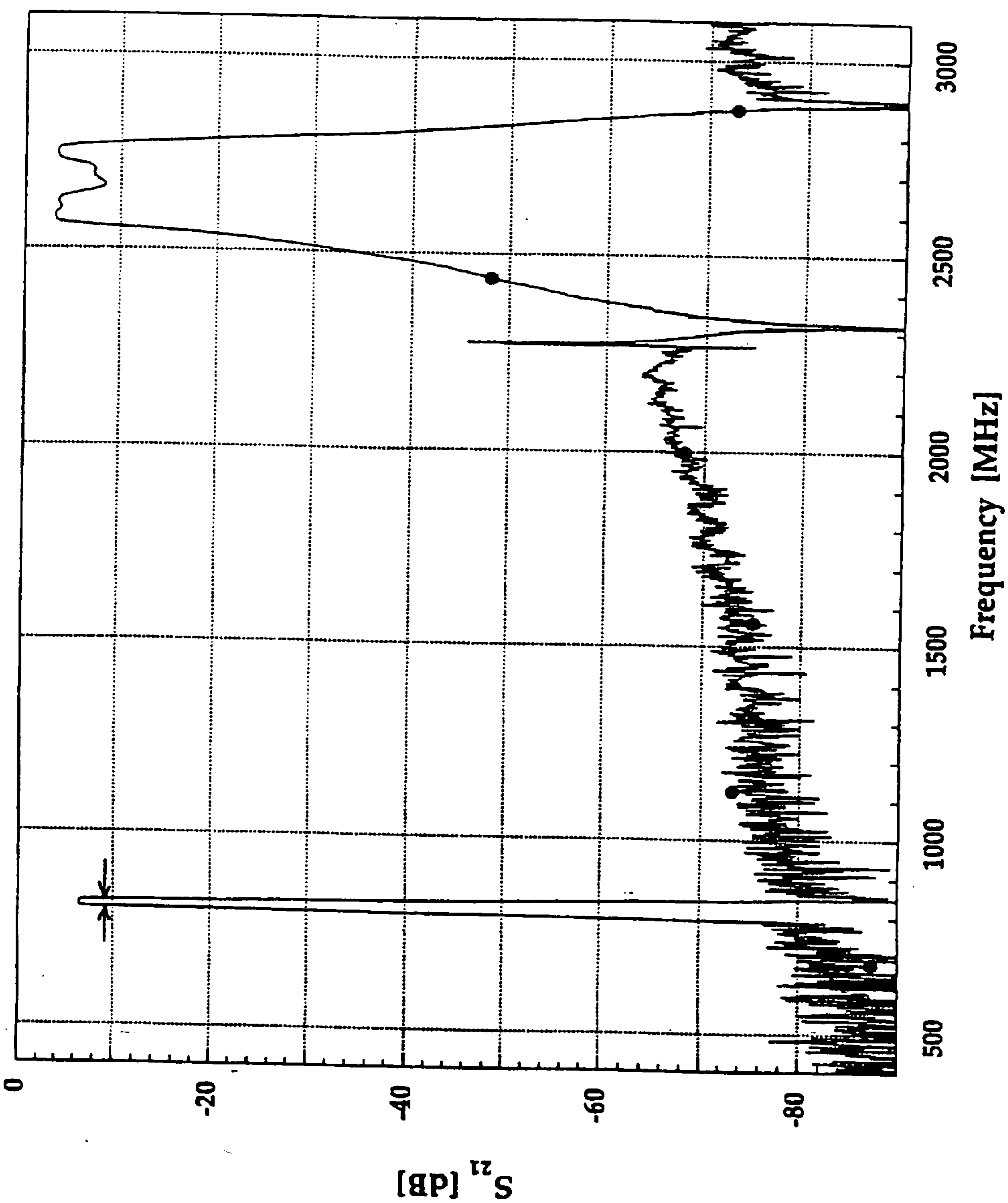


FIG. 2b

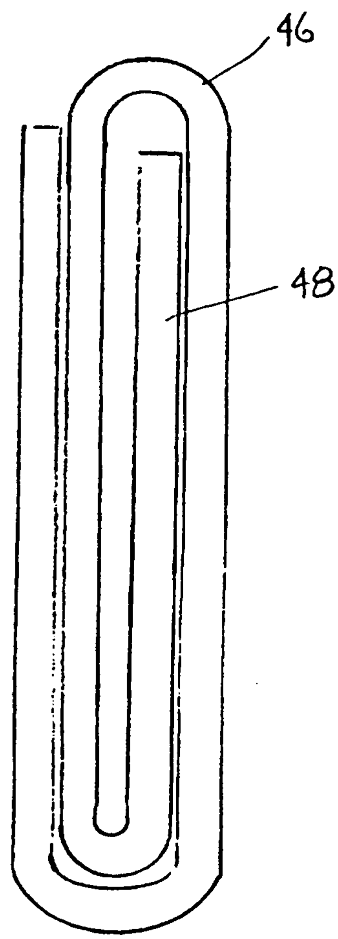


FIG. 3

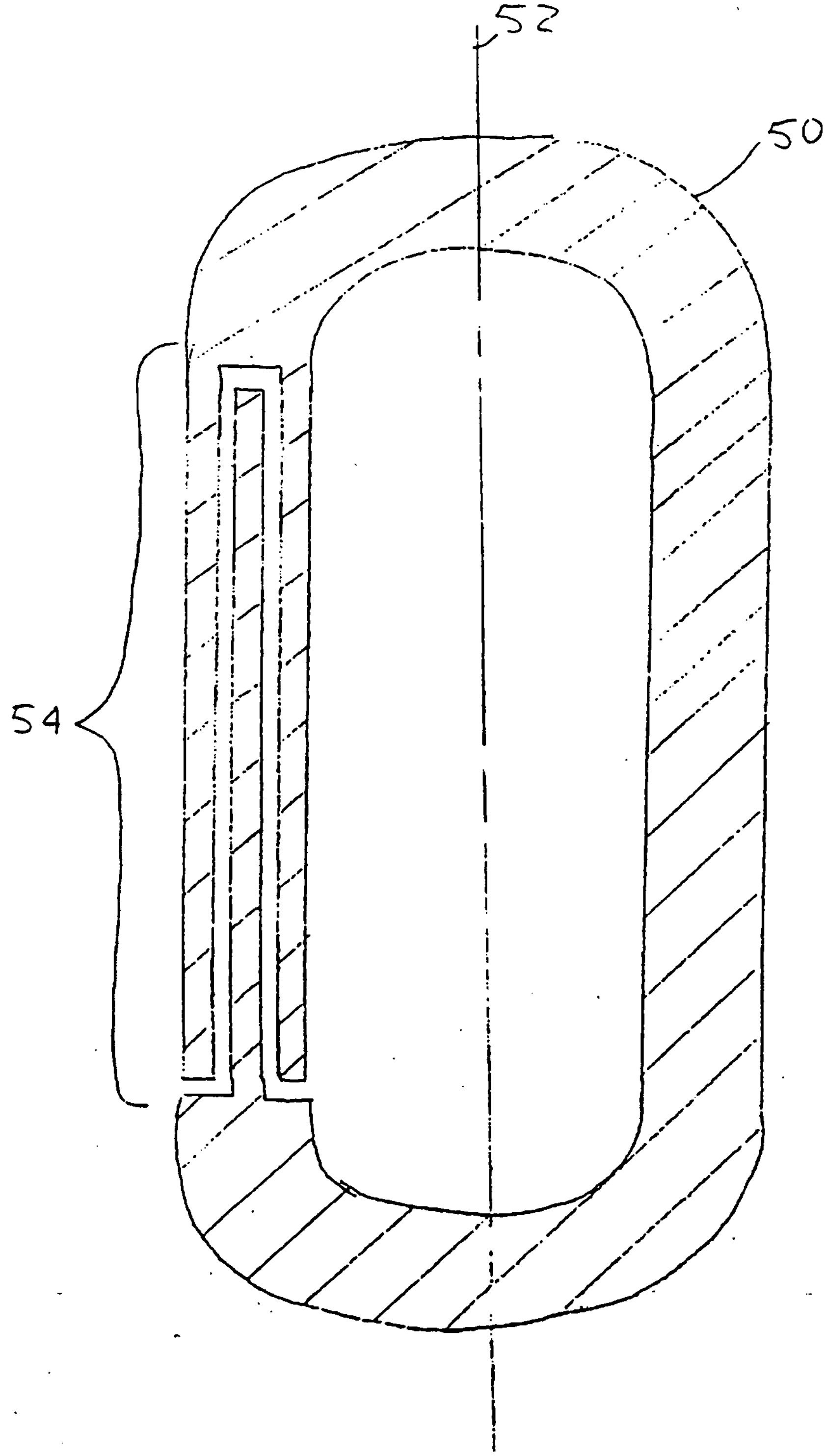


Fig. 4

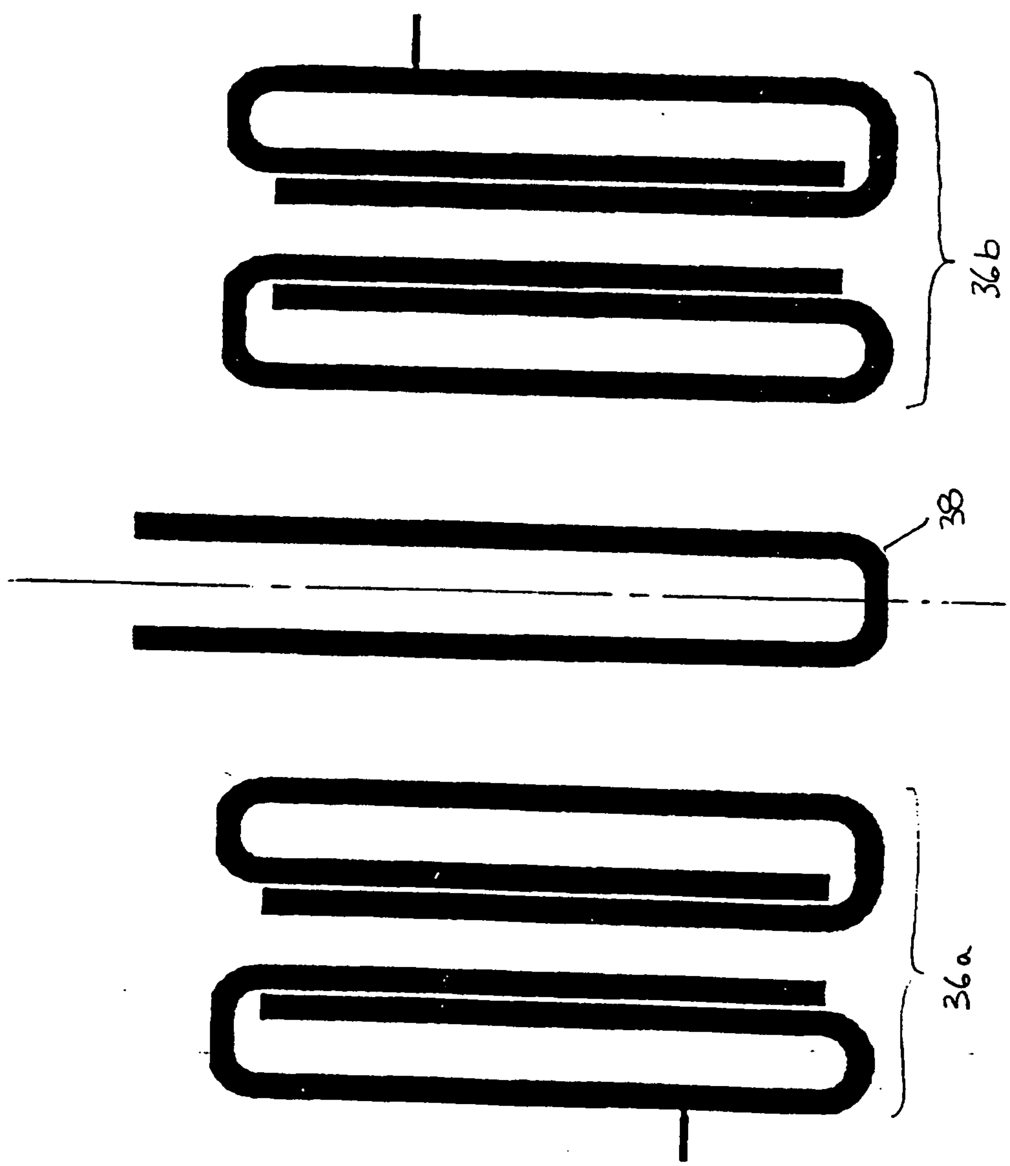
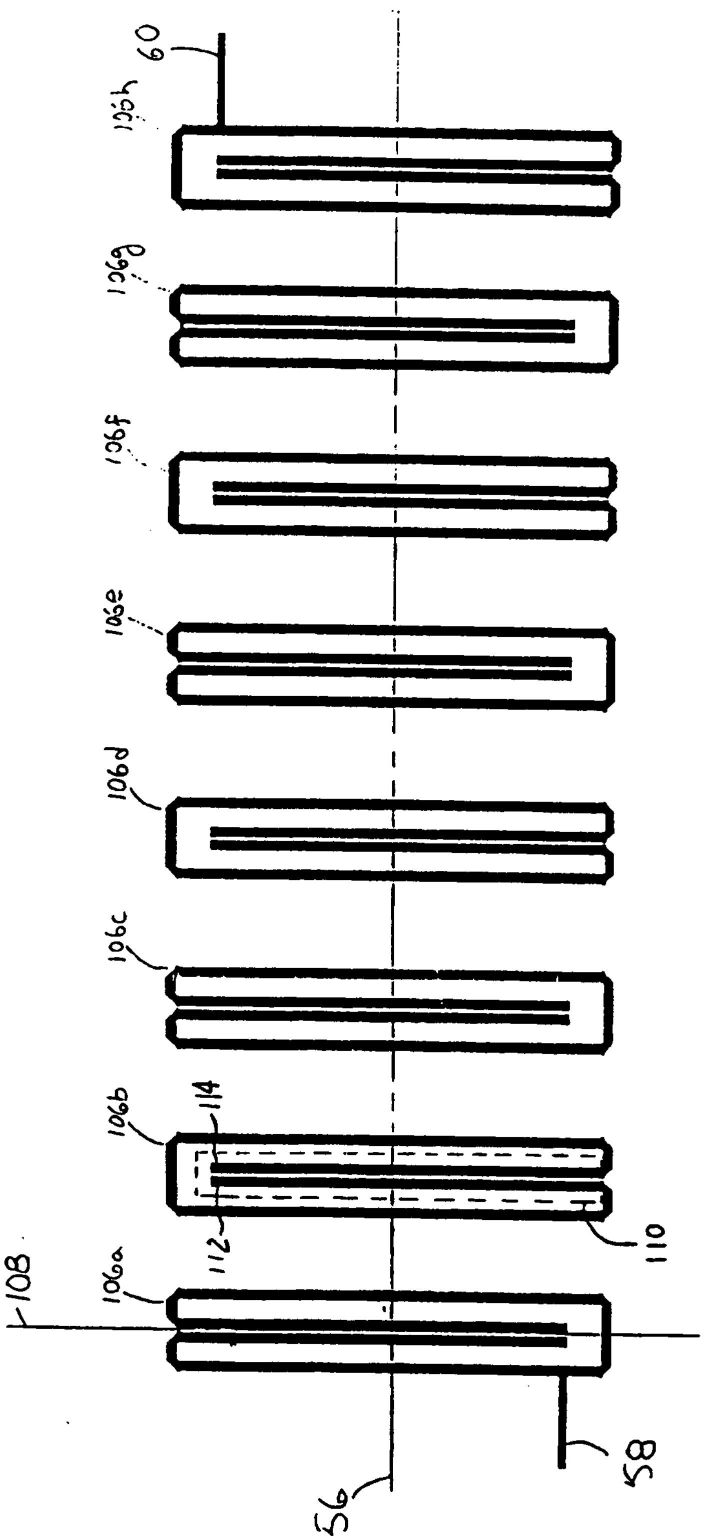


FIG. 5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106h
106g
106f
106e
106d
106c
106b
114
112
110
108
106a
56
58

FIG 6

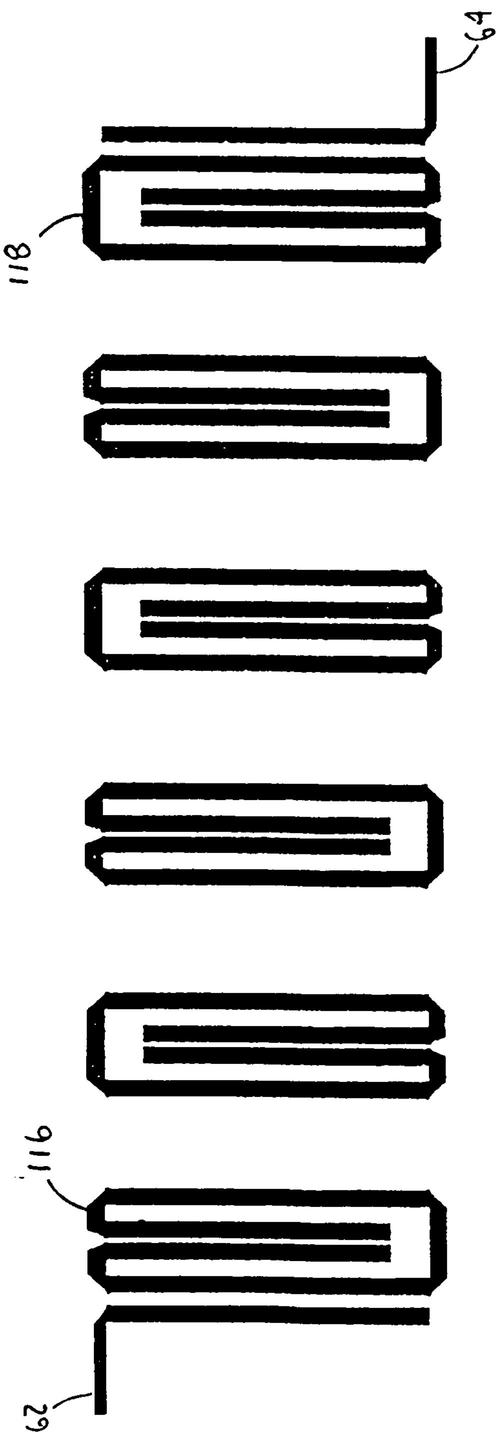

FIG. 7

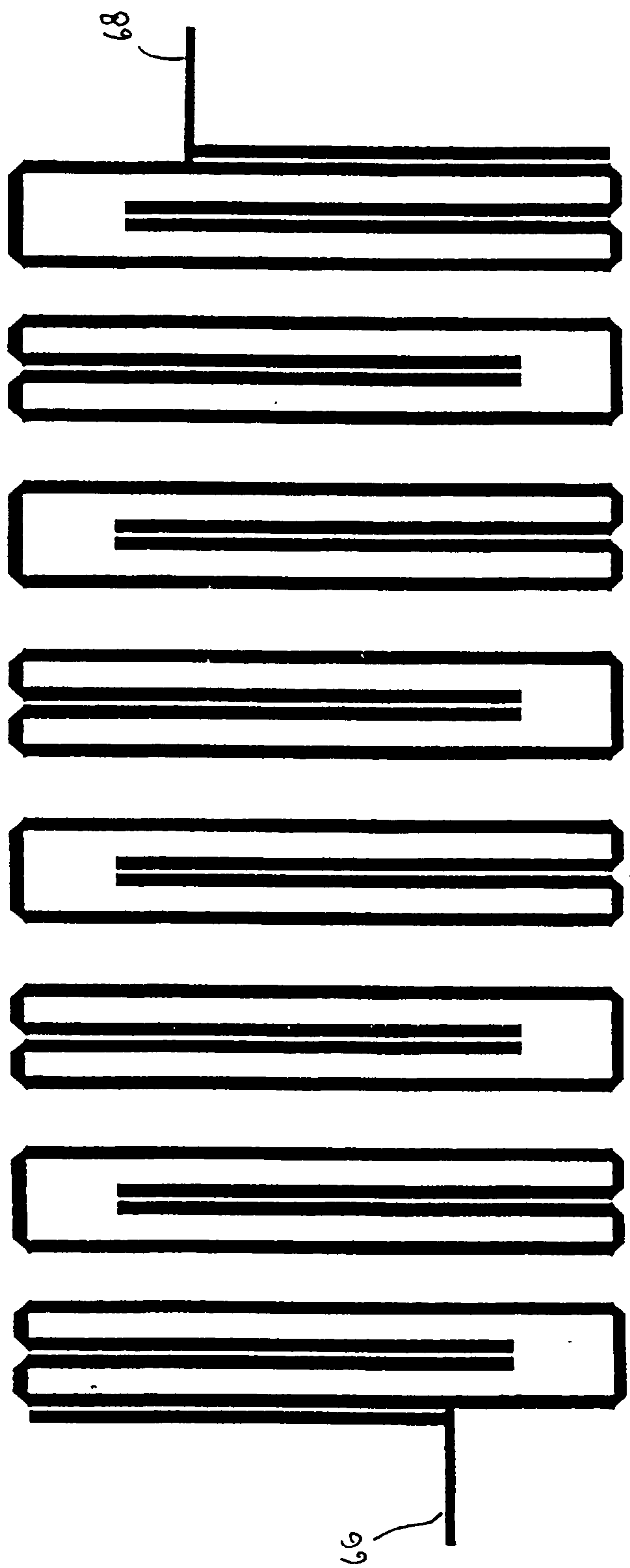

FIG. 8

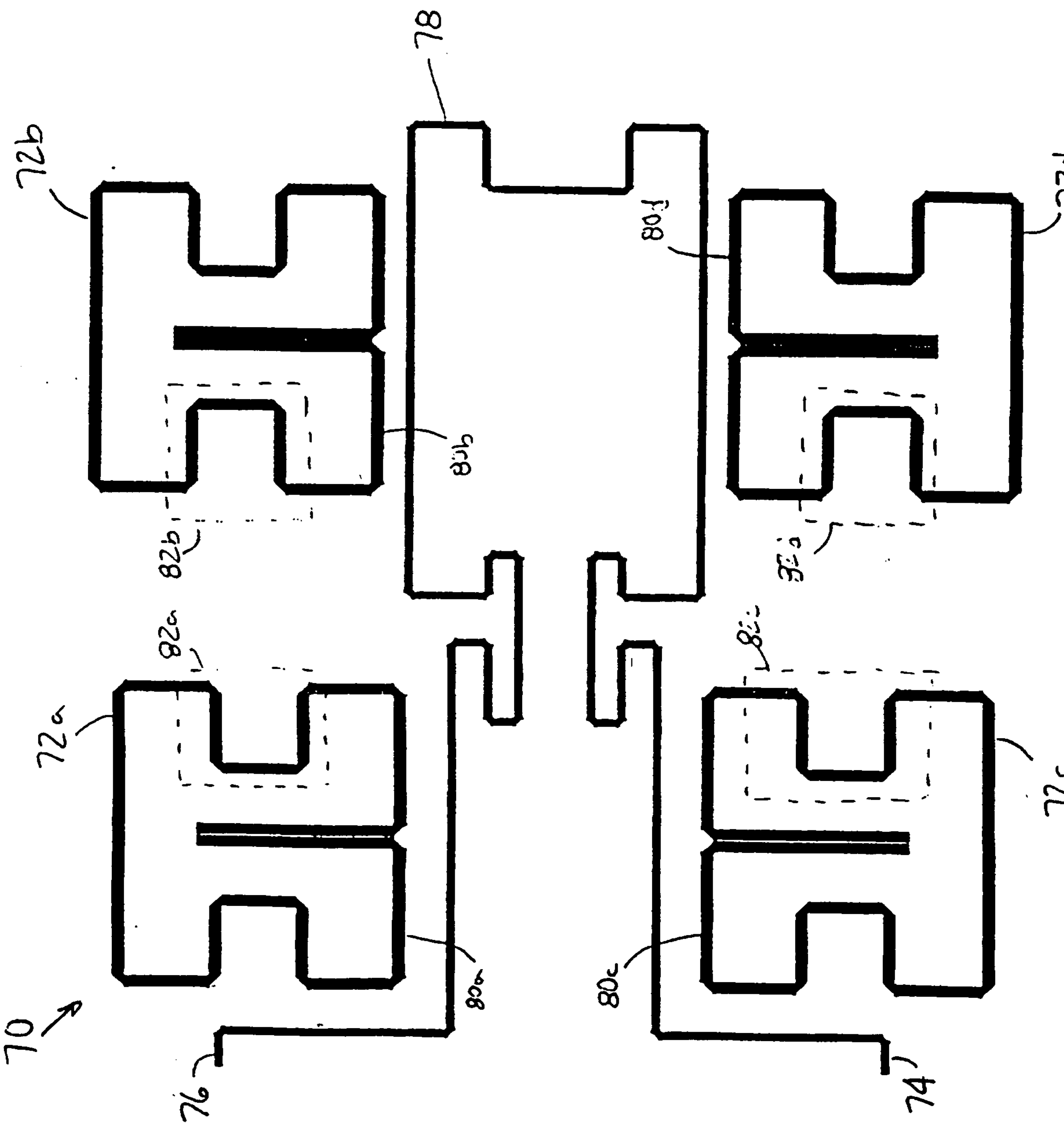

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/11172

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H01P 1/203; H01B 12/02
US CL :505/210, 701, 866; 333/204, 219, 99S
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 505/210, 700, 701, 866; 333/204, 205, 219, 99S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4,455,540 A (HENRIOT ET AL) 19 June 1984 (19/06/84), see fig. 5 & cols 3, ls 23-50.	1,2; 3,4
X	US 5,055,809 A SAGAWA ET AL 08 October 1991 (08/10/91), see figs. 9,10 & col 7, l. 6 - col 8, l. 11.	5
X	US 5,192,927 A LIN 09 March 1993 (09/03/93) see figs. 2(e) & 2(f) along with col 1, l. 60 - col 2, l. 16.	13,14,16,17
X	US 4,264,881 (DE RONDE) 28 April 1981 (28/04/81), see figs. 4e & 4g along with col 3 ls 45-50, as well as fig. 7b along with col 4, l. 44 - col 5, l. 4.	1,2; 3,4; 18-27

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
18 NOVEMBER 1997	09 DEC 1997

Name and mailing address of the ISA/US	Authorized officer
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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,512,539 (MATSUURA ET AL) 30 April 1996 (30/04/96), see figs 4-9 and description thereof.	7-12

CORRECTED VERSION*

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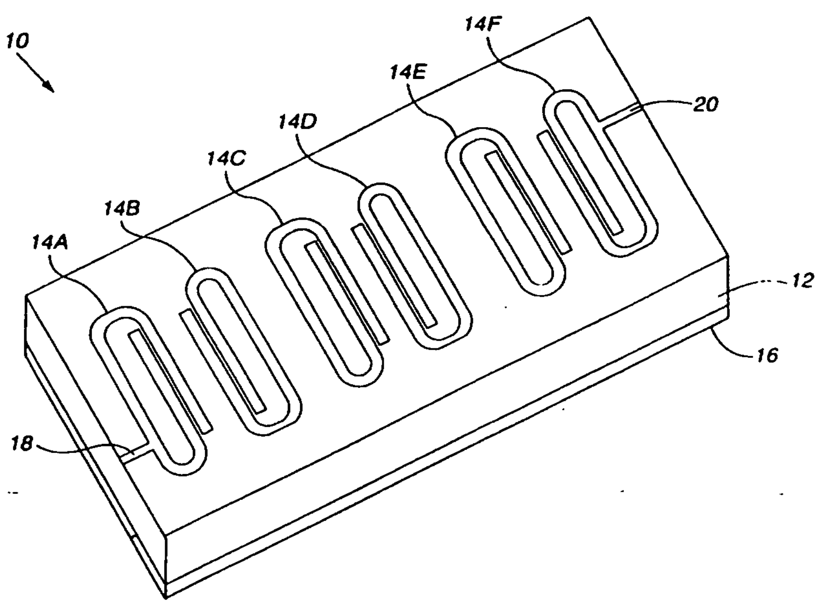
(54) Title: PLANAR RADIO FREQUENCY FILTER



(57) Abstract

A planar filter (10) for performing signal filtering at radio frequencies is provided. The planar filter can include asymmetrical resonators (14a-14f), wherein each resonator is asymmetrical about a longitudinal center axis (23a-23f) through the resonator. In addition, the resonators can be grouped in coupled pairs (22a-22c) such that the resonators in each coupled pair are asymmetrical about a longitudinal center axis (32a-32c) between the paired resonators. In addition, a coupling structure (66, 68) is provided that includes both distributed coupling and tapped coupling to a resonator. Further, a bandstop filter device (70) is provided that includes coupling between resonators (72a-72d) in the filter.

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PLANAR RADIO FREQUENCY FILTER

FIELD OF THE INVENTION

The invention relates in general to radio frequency filter structures and, more particularly, to radio frequency filter structures having a planar configuration.

BACKGROUND OF THE INVENTION

A planar filter is a radio frequency filtration device having all of its circuitry residing within a relatively thin plane. To achieve this, planar filters are generally implemented using flat transmission line structures such as microstrip and stripline transmission lines. These transmission line structures normally include a relatively thin, flat conductor separated from a ground plane by a dielectric layer. Planar filters have been of interest in recent years because of their relatively small size, low cost and ease of manufacture.

Planar filters ca be comprised of one or more resonator elements. A resonator element is a transmission line configuration that is known to "resonate" at a certain center frequency. In general, a plurality of these resonator elements are arranged to achieve a desired filter response. For example, the resonators can be arranged so that only a predetermined range of frequencies (and harmonics of such) are allowed to pass through the filter from an input port to an output port. This type of filter is known as a "bandpass" filter and the predetermined range of frequencies is known as the pass band of the filter. In another arrangement, the resonators can be configured so that all frequencies are allowed to pass from an input port to an output port except for a predetermined range of frequencies (and harmonics of such). This type of filter is known as a "bandstop" filter and the predetermined range of frequencies is known as the stop band of the filter.

Planar filters, as well as the other filter types, have a number of important performance criteria. For example, it is generally desirable that a bandpass filter display very low insertion loss in the pass band of the

filter. Outside of the pass band, however, high rejection is desirable. Conversely, a bandstop filter requires relatively little loss outside of the stop band and a high amount of rejection within the stop band.

In many applications, both bandpass and bandstop filters require a relatively sharp cutoff at the band edges. That is, the transition from a low loss condition to a high loss condition should take place over a relatively narrow range of frequencies. Sharp cutoff is required, for example, in applications where a relatively large number of frequency bands exist within a given frequency range, to separate out the individual bands. The sharpness of the filter response cutoff depends upon such things as, for example, the quality factor of the filter (i.e., the Q factor), the number and type of resonators that are being used in the filter, the materials used in the filter, and the arrangement of the resonators in the filter.

Some applications now require filter structures that are very small in size. For example, a mobile handset in a cellular or PCS communications system requires a filter for preselection of a predetermined operational frequency range. Because the size of these handsets is constantly being reduced, the area that can be dedicated to filter units is correspondingly being reduced. In addition, as increased functionality is being added to these handsets, the space available for filters is further reduced. Another application requiring small sized filters is monolithic microwave integrated circuits (MMICs). MMICs generally comprise full microwave subsystems, such as a multichannel microwave receiver, disposed within a single small package. As is apparent, large, bulky filters could not be used in such systems.

A third application requiring small sized filters is tower-mounted receiver front ends used in wireless base stations. The close proximity of the receiver front end to the antenna minimizes the noise figure of the microwave

signal receiving system. For this application, the filters must be located in a temperature-controlled enclosure to shield them from ambient weather conditions. By utilizing small sized planar filters, rather than conventional cavity filters, the cost of maintaining this enclosure, as well as potentially deleterious effects of wind loading are reduced.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a planar filter structure having a reduced size.

It is another object of the present invention is to provide a planar filter structure having a relatively high Q value.

It is yet another object of the present invention to provide a planar filter structure having relatively sharp cutoff at the band edges.

It is still another object of the present invention to provide all of the above advantages within a single filter unit that is relatively inexpensive to produce.

The present invention relates to structures for providing bandpass and/or bandreject filter responses in radio frequency systems. The structures provide desired filter responses while occupying a relatively small amount of real estate on an underlying substrate. In this regard, the filter structures of the present invention are valuable in applications having a limited amount of available space. In addition, the filter structures are relatively easy and inexpensive to manufacture. The inventive structures can be implemented in a variety of different transmission line types including, for example, microstrip transmission line, stripline transmission line, and suspended substrate transmission line.

In one aspect of the present invention, a planar filter is provided having a plurality of resonator elements. Lines are provided for coupling energy into and out of the filter. In accordance with the invention, at

least one of the input and output structures uses both distributed line coupling and tapped coupling to perform the desired coupling function. In a related aspect of the invention, the coupling type used at the input of the filter is different from that used at the output of the filter. That is, for example, distributed coupling is used at the input while tapped coupling is used at the output. Alternatively, one of the input or the output can include both distributed and tapped coupling while the other includes just one type of coupling.

In another aspect of the present invention, a planar bandpass filter is provided that includes a plurality of resonating elements arranged in an approximately linear fashion. Each pair of adjacent resonating elements includes a longitudinal center axis therebetween. An odd number of the pairs include elements that are asymmetrical about the corresponding longitudinal center axis. It has been discovered that utilizing an odd number of asymmetrical pairs improves the rejection characteristics of the filter for a given number of resonating elements. In one embodiment, the resonators include novel "paper clip" resonators having a plurality of substantially parallel legs that are interconnected by folds.

In another aspect of the present invention, a planar bandstop filter is provided that comprises a plurality of resonating elements, wherein at least two of the resonating elements are directly coupled to one another. In one embodiment, a first side of a first resonator is coupled to a second resonator and a second side of the first resonator is coupled to a third resonator. The coupling to the second resonator is stronger than the coupling to the third resonator.

In another aspect of the present invention, a planar bandstop filter is provided that includes a plurality of resonating elements coupled to a through line, wherein a first of the resonating elements is directly coupled to a second of the resonating elements. The through line

connects the input of the filter to the output of the filter. The coupling between the first and second resonating elements is adapted to improve the rejection characteristics of the filter. In one embodiment of the invention, anisotropic coupling between resonators is achieved by utilizing resonators having a distributed capacitance between opposite ends of a conductor. To achieve a decreased amount of coupling between a first resonator and a second resonator, for a given distance between the resonators, a side of the first resonator that includes the distributed capacitance faces the second resonator. To achieve reduced coupling between a first and a third resonator, a meandering line is introduced into the side of the first resonator that faces the third resonator. The meandering line increases the effective distance between the first resonator and the second resonator (and hence decrease the coupling) while the actual distance between the resonators remains the same.

In yet another aspect of the present invention, a planar filter is provided that includes a resonator having a first, second, and third leg that are all substantially parallel to one another. The third leg is located between outer edges of the first and second leg. The first and second leg are connected by a first fold while the second and third legs are connected by a second fold. The "fold" can include, for example, a bend in the transmission line conductor. The resonator is asymmetrical about a first longitudinal center axis. The third leg can be spaced from the first leg so as to create a distributed capacitance between the legs. This distributed capacitance allows the overall dimensions of the resonator to be reduced. The resonator can also include a fourth leg that is spaced from the second leg to create a distributed capacitance therewith.

In still another aspect of the present invention, a planar filter is provided that includes a first resonator element and a second resonator element. The first

resonator element includes a first conductor with a first portion at a first end and a second portion at a second end. The conductor has a bend so that the first portion is opposite the second portion over at least a fraction of its length. The second element includes a third portion that is located between the first portion and the second portion of the first resonator element. In one embodiment, a dual element hairpin resonator is provided that includes two hairpin shaped resonators having their fingers interdigitally arranged.

In all aspects of the present invention, the resonators and other structures can be made out of superconducting materials to increase the Q value of the filters and reduce radiation from the resonators.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1a is an isometric view of a six pole bandpass filter in accordance with the present invention;

Fig. 1b is a top view of the metallization pattern for the filter of Fig. 1a illustrating a plurality of three leg "paper clip" resonators;

Fig. 2a is a computer simulated graph showing a predicted response of the filter of Figs. 1a and 1b;

Figs. 2b is a graph illustrating a measured response (uncalibrated) of the filter of Figs. 1a and 1b showing the lack of even-ordered harmonics in the filter response;

Fig. 3 is a top view of the metallization pattern of a four leg "paper clip" resonator in accordance with the present invention;

Fig. 4 is a top view of the metallization pattern of a resonator having an interdigital coupling structure in accordance with the present invention;

Fig. 5 is a top view of the metallization pattern of a five pole filter having two coupled resonator pairs and a single symmetric resonator in accordance with the present invention;

Fig. 6 is a top view of the metallization pattern of an eight pole band pass filter using "pinched end" resonators and having tapped input and output lines in accordance with the present invention;

Fig. 7 is a top view of the metallization pattern of a six pole bandpass filter using "pinched end" resonators and having input and output lines utilizing distributed coupling in accordance with the present invention;

Fig. 8 is a top view of the metallization pattern of an eight pole bandpass filter using "pinched end" resonators and having input and output lines utilizing both tapped and distributed coupling in accordance with the present invention; and

Fig. 9 is a top view of the metallization pattern of a four pole bandstop filter utilizing coupled "pinched end" resonators in accordance with the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The present invention relates to structures for providing bandpass and/or bandreject filter responses in radio frequency systems. The structures provide desired filter responses while occupying a relatively small amount of real estate on an underlying substrate. In this regard, the filter structures of the present invention are valuable in applications having a limited amount of available space. In addition, the filter structures are relatively easy and inexpensive to manufacture. The inventive structures can be implemented in a variety of different transmission line types including, for example, microstrip transmission line, stripline transmission line, and suspended substrate transmission line. It should be appreciated that the term "radio frequency", as used herein, is meant to apply to all portions of the electromagnetic spectrum that are capable of propagation on the transmission structures disclosed herein, including, for example, high frequency (HF), very high frequency (VHF), microwaves, millimeter waves, and submillimeterwaves.

Fig. 1a illustrates a six pole microstrip bandpass filter 10 in accordance with one embodiment of the present invention. The bandpass filter of Fig. 1a was originally disclosed in provisional U.S. Patent Application Serial No. 60/020,863 entitled "ASYMMETRIC MICROWAVE RESONATING DEVICE" which is incorporated herein by reference. As illustrated, the filter 10 includes a planar substrate material 12, a ground plane 16 underlying the substrate 12, a plurality of resonator elements 14a-14f, an input line 18, and an output line 20. In operation, an electromagnetic signal is delivered to input line 18 from an external source after which it is acted upon by the resonators 14a-14f. The resonators 14a-14f allow certain frequencies in the electromagnetic input signal to couple through from the input line 18 to the output line 20, while other frequencies are rejected (i.e., reflected back out through input line 18).

Fig. 1b is a top view of the metallization pattern deposited on the top surface of substrate 12 showing the general configuration of the resonators 14a-14f. The resonators 14a-14f each include a single continuous transmission line conductor formed into a shape resembling that of a paper clip, and hence are called "paper clip" resonators. The paper clip resonators illustrated in Fig. 1b each have three parallel legs that are connected by folds at the ends of the resonator. The electrical length of each resonator is approximately equal to one-half of a guide wavelength (i.e., $\lambda g/2$) at the center frequency of the resonator. As illustrated in Fig. 1b, each resonator 14a-14f includes a portion 24 wherein a first leg 26 at a first end of the conductor is spaced from a third leg 28 at a second end of the conductor by a relatively narrow gap 30. The dimensions of the gap 30 are chosen so that a desired distributed capacitance exists between the ends 26, 28 of the conductor. In a typical embodiment, the width of the gap 30 is between 0.1 and 10 mils. Because of the presence of an additional capacitance in the resonator, the

size of the resonator can be reduced while maintaining a desired resonating frequency.

The spacing between successive resonators is determined based upon a coupling required to achieve a desired filter response. If the resonators are placed too closely to one another, the resonators will be too tightly coupled, resulting in an undesired shift or spread in the resonance characteristic of the filter.

As illustrated in Fig. 1b, the resonators 14a-14f are each asymmetrical about a corresponding longitudinal center axis 23a-23f. The longitudinal center axes 23a-23f are substantially perpendicular to the direction 29 of energy flow through the filter. In addition to the elemental asymmetry, the resonators 14a-14f are also arranged into coupled pairs 22a-22c that are each asymmetrically arranged about a corresponding central axis 32a-32c extending longitudinally between the resonators. Because the arrangement between each pair 22a-22c is asymmetrical, the coupling between the resonators within each pair is reduced, thereby allowing the resonators within each pair to be spaced more closely together. This decreased spacing between the resonators in each pair reduces the overall dimensions of the filter 10. In conceiving of the present invention, it has been determined that an optimal filter response is achieved when the number of "flips" within the chain of resonators is odd. A "flip" is defined as a double rotation of a resonator about two axes of rotation. For example, the positioning of resonator 14b in Fig. 1b can be obtained by rotating resonator 14a once about longitudinal center axis 32a and once about latitudinal axis 34. The positioning of resonator 14c can be obtained by a similar double rotation of resonator 14b and so on. In accordance with the present invention, the latitudinal axis 34 does not have to be centered on the element. As described above, in a preferred embodiment of the present invention, the number of flips is odd. It has been discovered that use of an odd number of flips and a

tapped input and/or output produces zeros in the transfer function of the filter that occur at the band edges of the filter response resulting in sharper cutoffs at the band edges than are normally obtainable.

Input 18 and output 20 are each located on either side of and substantially equidistant from the latitudinal center axis 34. As illustrated, the input 18 and the output 20 each comprise a conductively coupled tap on a corresponding resonator element 14a, 14f. The position of the tap on the resonator depends on the desired freqency, bandwidth, ripple, filter order, and the width of the resonator line.

The width of the conductor forming each resonator 14a-14f preferably produces a line impedance ranging from about 10 to about 80 ohms. As discussed above, the distance between the first leg 26 and the third leg 28 is typically from about 0.1 mil to about 10 mils. The distance between a second leg 27 and the third leg 28 is typically from about 1 to about 5 line widths. The distance 100 between adjacent resonators in a given pair typically ranges from about 1 to about 250 mils. The distance 102 between adjacent pairs typically ranges from about 2 to about 400 mils.

The various components of the filter of Figs. 1a and 1b can have a variety of compositions in accordance with the present invention. The resonator conductors and ground plane can be composed of a variety of conducting and superconducting materials, including (a) nonsuperconducting metals, such as gold, copper, and silver, and (b) high temperature superconductors, such as ytrium barium copper oxide (YCBO) and thallium barium calcium copper oxide (TBCCO). Use of superconducting materials is advantageous because they reduce metallization losses in the filters, thus enabling higher Q values to be observed in the filters. This means the filters have lower insertion loss in the passband and sharper out-of-band attenuation. The dielectric substrate can be composed of any dielectric

material, such as air, alumina, quartz, sapphire, lanthanum aluminate (LAO), magnesium oxide (MgO), teflon (PTFE), teflon based board materials such as "Duroid" sold by Rogers Corporation, gallium arsenide (GaAs), and other common circuit board materials such as FR4/G10.

Fig. 2a is a computer simulated response characteristic for the filter illustrated in Figs. 1a and 1b. As shown, the simulated filter response has a very low loss 42 in the passband and very sharp cutoffs 40a, 40b at the edges of the passband. In addition, the response is relatively symmetric about a center frequency. The sharp cutoffs 40a, 40b are the result of zeros in the transfer function of the filter that are created due to tapping and having an odd number of “flips” between the resonators. The zeros are evident in the simulated response as the depressions 44a and 44b in the skirt of the graph of Fig. 2a.

Fig. 2b is a graph showing the measured response of the filter (uncalibrated) over a large frequency range. As shown, rejection is very high at the even ordered harmonics (i.e., >70 dB). In addition, parasitics are substantially suppressed in the vicinity of the passband. In addition, calibrated measurements of insertion loss in the passband indicate that the loss is below 0.3 dB.

The design principles used to reduce circuit dimensions in the filter of Figs. 1a and 1b are not limited to the use of the "paper clip" resonator structure disclosed therein. In fact, any resonator design that is asymmetrical about a longitudinal center axis through the element can be used in accordance with the present invention. For example, the element 46 of Fig. 3 can be used in the filter of Figs. 1a and 1b. Resonator 46 is similar to the "paper clip" resonators 14a-14f of Figs. 1a and 1b, but includes a fourth leg 48 that provides further distributed capacitance in the resonator 46. This additional distributed capacitance allows the overall

dimensions of resonator 46 to be further reduced while still achieving a desired resonant frequency.

Fig. 4 illustrates another resonator design that can be used in the filter of Figs. 1a and 1b. Resonator 50 is asymmetrical about a longitudinal center axis 52 passing through the resonator. On one side of the resonator 50, an interdigital coupling structure 54 is provided for creating the required distributed capacitance. It should be appreciated that the resonator embodiment illustrated in Fig. 4 can include any number of interdigital fingers in coupling structure 54 and is not limited to the illustrated number (i.e., 3).

Fig. 5 is the top view of the metallization pattern for a five pole bandpass filter in accordance with the present invention. As illustrated, the filter of Fig. 5 includes two pair 36a, 36b of asymmetrical resonator elements on either side of a single symmetrical resonator element 38 having a "hairpin" shape. By using a symmetrical resonator element 38 in conjunction with the asymmetrical coupled pairs 36a, 36b, a bandpass filter having an odd number of poles is achievable. In fact, any combination of symmetrical resonator elements and asymmetrical pairs is possible in accordance with the present invention.

Fig. 6 illustrates the metallization pattern for an eight pole filter in accordance with the present invention. The filter of Fig. 6 utilizes "pinched end" resonators 106a-106h that are each symmetrical about a corresponding longitudinal center axis 108. Each "pinched end" resonator 106a-106h includes a central portion 110 wherein a first end portion 112 of a conductor is spaced from a second end portion 114 of the conductor to form a distributed capacitance therebetween. As discussed previously, this distributed capacitance results in smaller resonators 106a-106h for a given resonant frequency. When constructed from superconducting materials, the "pinched end" resonators display high-Q values with very little radiation loss,

despite the fact that each resonator has six 90 degree bends. It is believed that the high conductivity of the superconducting material insures that fields are "contained" within the dielectric substrate material, which minimizes radiation at the bends. Similarly, the distributed capacitance between the first end portion 112 and the second end portion 114 of the conductor further contains the fields and reduces radiation.

As shown, each successive resonator in the filter is "flipped" with respect to the previous resonator and the total number of "flips" is odd. The filter of Fig. 6 includes tapped input and output lines 58, 60 similar to those in the filter of Figs. 1a and 1b. One important benefit of using tapped input/output lines is improved near out band rejection by introducing attenuation zeros.

Fig. 7 illustrates a six pole bandpass filter having "pinched end" resonators that utilize input and output lines 62, 64 that are coupled to an input resonator 116 and an output resonator 18, respectively, using distributed coupling. One important benefit of using distributed coupling in the input and/or output is the ability to optimaize the return loss by perturbing the input/output couplings to the resonator. In conceiving of the present invention, it was determined that enhanced performance could be achieved by combining tapped coupling and distributed coupling in the input and/or output structures. That is, dual coupling arrangements provide benefits associated with both coupling methods. Fig. 8 illustrates an eight pole bandpass filter that includes both distributed and tapped coupling on both an input 66 and an output 68. It should be appreciated that, in accordance with the present invention, the type of coupling used at the input of a filter can be different from the type used at the output of the filter. For example, the input may use distributed coupling, while the output uses tapped coupling. Also, the input can use a dual coupling arrangement, while the output uses a single coupling type.

Fig. 9 illustrates a four pole bandstop filter 70 in accordance with the present invention. The filter 70 includes four "pinched end" resonators 72a-72d each coupled to a meandering through line 78. The filter 70 als o includes an input port 74 and an output port 76 for coupling energy into and out of the meandering through line 78. During operation, a radio frequency signal is applied to the input port 74 of the filter from an exterior source and begins to propagate along the meandering through line 78. As the radio frequency signal passes one of the resonators, undesired frequency components in the signal are drawn out of the signal by the resonating action of the resonator.

By utilizing multiple identical resonators, the filter 70 can achieve a bandpass characteristic having relatively sharp cutoffs at the band edges. In addition, in conceiving of the present invention, it was determined that further sharpening of the cutoffs could be achieved by introducing coupling between the resonators of the filter. For example, in the filter 70 of Fig. 9, each resonator is directly coupled to an opposing resonator. That is, resonator 72a is directly coupled to resonator 72c, and resonator 72b is directly coupled to resonator 72d. By introducing this coupling between opposing elements, additional zeros are formed in the transfer function of the filter 70 at the edges of the stopband.

To form the required zeros in the transfer function, it is important that coupling between the aforementioned pairs be optimized while coupling between other pairs, such as between resonator 72a and resonator 72b, or between resonator 72c and resonator 72d, be minimized. In conceiving of the present invention, it was appreciated that anisotropic coupling characteristics could be achieved by properly choosing the type and arrangement of the elements. For example, it was found that decreased coupling could be achieved between a first and a second pinched end resonator by arranging the resonators so that

the side having the pinched end on the first resonator faces the same side on the second resonator. For example, with reference to Fig. 9, side 80a of resonator 72a faces side 80c of resonator 72c and side 80b of resonator 72b faces side 80d of resonator 72d.

In addition to the above, it was appreciated that coupling could be reduced between two resonators by using a meandering line on each of the coupled sides between the resonators. For example, with reference to Fig. 9, resonators 72a and 72b both include meandering lines 82a and 82b, respectively, on the sides facing one another. The same applies to resonators 72c and 72d. By using a meandering line, the effective distance between the elements is increased, thereby decreasing coupling between the elements, while the actual distance between the elements remains the same. In this way, the overall dimensions of the filter 70 can be reduced while still achieving a desired low coupling between certain elements.

To achieve a desired filter response, a predetermined electrical distance must be provided on through line 78 between the coupling points of the four resonators 72a-72d. To reduce the overall dimensions of the filter 70, a meandering through line 78 has been implemented. By having the through line 78 follow a winding path, rather than a straight one, the elements 72a-72d can be spaced closer together while still maintaining the desired electrical length between coupling points. This reduces the size of the filter.

By introducing coupling between the resonator elements, a quasi-elliptic filter response is achieved rather than a Chebyshev or Butterworth filter response. Because a quasi-elliptic filter response, having very sharp cutoffs, is achieved, the number of resonators required for sharp stopband cutoff characteristics is reduced. Reducing the number of resonators naturally reduces the size of the filter.

It should be appreciated that the metallization structures disclosed herein can be produced on a substrate by well known deposition and masking techniques. In addition, sheet metal stamping and other processes can be used to create slab line or other airloaded transmission structures.

Although the present invention has been described in conjunction with its preferred embodiments, it is to be understood that modifications and variations may be resorted to without departing from the spirit and scope of the invention as those skilled in the art readily understand. For example, the techniques and structures described above are not limited to use with half-wavelength resonators and can also be used with other resonator types, such as quarter-wavelength resonators. Such modifications and variations are considered to be within the purview and scope of the invention and the appended claims.

What is claimed is:

1. A planar filter for radio frequency energy, comprising:

a plurality of resonating elements separated from a ground structure by a dielectric layer, the plurality of resonating elements including input and output resonating elements; and

an input for radio frequency energy in communication with the input resonating element and an output for the radio frequency energy in communication with the output resonating element, wherein at least one of the input and output has a first portion spaced from a corresponding one of the input and output resonating elements for distributively coupling a first component of the radio frequency energy between the first portion and the corresponding one of the input and output resonating elements and a second portion physically connected to the corresponding one of the input and output resonating elements for tap coupling a second component of the radio frequency energy between the second portion and the corresponding one of the input and output resonating elements such that the first component of the radio frequency energy substantially excludes the second component of the radio frequency energy.

2. The planar filter of Claim 1, wherein:

said plurality of resonating elements are arranged in an approximately linear fashion and each pair of adjacent resonating elements has a corresponding longitudinal center axis located therebetween, the corresponding longitudinal center axis being substantially normal to a direction of flow of radio frequency energy through the filter, wherein a number of the pairs of adjacent resonating elements are asymmetrical to one another relative to the corresponding longitudinal center axis, and wherein the number of pairs of adjacent resonating elements that are asymmetrical to one another relative to the corresponding longitudinal center axis is odd.

3. A planar filter for radio frequency energy, comprising:

a plurality of resonating elements separated from a ground structure by a dielectric layer, said plurality of resonating elements including an input resonating element and an output resonating element;

an input for coupling radio frequency energy from an exterior environment to said input element; and

an output for coupling radio frequency energy from said output resonating element to said exterior environment;

wherein one of said input and said output includes a first conductive portion that is physically connected to a corresponding one of said input resonating element and said output resonating element for conductively transferring radio frequency energy therewith and the other of said input and said output includes a second conductive portion that is spaced from a corresponding one of said input resonating element and said output resonating element for radiatively transferring radio frequency energy therewith.

4. The planar filter of Claim 3, wherein:

said other of said input and said output also includes a third conductive portion that is physically connected to a corresponding one of said input resonating element and said output resonating element for conductively transferring radio frequency energy therewith.

5. A planar bandpass filter for radio frequency energy, comprising:

a plurality of resonating elements arranged in an approximately linear fashion, wherein each pair of adjacent resonating elements has a corresponding longitudinal center axis located therebetween, the corresponding longitudinal center axis being substantially normal to a direction of flow of radio frequency energy through the filter, wherein a number of the pairs of adjacent resonating elements are asymmetrical to one another relative to the corresponding longitudinal center axis, and wherein the number of pairs

of adjacent resonating elements in the plurality of resonating elements that are asymmetrical to one another relative to the corresponding longitudinal center axis is odd.

6. The planar filter of Claim 5, wherein at least one resonating element in the plurality of resonating elements has a plurality of legs and folds, wherein a first leg, a second leg, and a third leg are substantially parallel to one another, the first and second legs defining an outer boundary of the resonating element and the third leg being located between an outer edge of the first leg and an outer edge of the second leg, and wherein the first and second legs are connected by a first fold and the second and third legs by a second fold, the second fold being different from the first fold, and wherein the at least one resonating element is asymmetrical about a longitudinal center axis through the center of the resonating element that is substantially normal to a direction of flow of radio frequency energy through the filter.

7. The planar filter of Claim 5, wherein at least one resonating element in the plurality of resonating elements includes a superconducting material.

8. The planar filter of Claim 7, wherein:

said superconducting material is disposed in a continuous line having a third portion, a fourth portion, and a total length, wherein said third portion is spaced apart from and approximately parallel to said fourth portion to form a distributed capacitance between said third portion and said fourth portion.

9. The planar filter of Claim 8, wherein the length of said third portion that is adjacent to said fourth portion is approximatiely 10% of the total length.

10. The planar filter of Claim 8, wherein the distance between the third portion and the fourth portion of the line is approximately 5 mils.

11. The planar filter of Claim 8, wherein the distributed capacitance is approximately 2 picofarads.

12. The planar filter of Claim 8, wherein the planar filter has an unloaded Q of at least about 25,000.

13. A planar bandstop filter for radio frequency energy, comprising:

a plurality of resonating elements, wherein a distance between at least two of the resonating elements is sufficient to permit radio frequency energy to be transmitted by direct coupling between the at least two resonating elements when radio frequency energy is applied to the filter.

14. The planar bandstop filter of Claim 13, wherein a first side of a first resonating element directly couples to a second resonating element and a second side of the first resonating element directly couples to a third resonating element, the first and second sides being different from one another, such that the first side passes a first portion of the radio frequency energy to the second resonating element and the second side passes a second portion of the radio frequency energy to the third resonating element.

15. The planar bandstop filter of Claim 14, wherein the energy level of the first portion exceeds that of the second portion.

16. The planar bandstop filter of Claim 13, wherein at least one of the resonating elements is formed from a continuous line of a superconducting material and wherein a first length of the line is spaced apart from a second length of the line to form a capacitance therebetween.

17. The planar bandstop filter of Claim 13, wherein an interresonator coupling coefficient between the at least two resonating elements is dependent on a bandwidth of said filter.

18. A planar bandstop filter for radio frequency energy, comprising:

an input for receiving radio frequency energy from an exterior environment;

an output for delivering radio frequency energy to said exterior environment;

a through transmission line for transferring radio frequency energy from said input to said output; and

a plurality of resonating elements coupled to said through transmission line, wherein a first of the resonating elements is directly coupled to a second of the resonating elements.

19. The filter of Claim 18, wherein:

said first resonating element and said second resonating element are both directly coupled to said through transmission line.

20. The filter of Claim 18, wherein:

said direct coupling between the first and second resonating elements is adapted to improve rejection characteristics within a stopband of the filter.

21. The filter of Claim 18, wherein:

said first and second resonating elements have an interresonator coupling coefficient therebetween that is dependent on a bandwidth of said filter.

22. The filter of Claim 21, wherein:

said first resonating element includes a transmission line conductor having a first end and a second end, said transmission line conductor being arranged such that a portion of the transmission line conductor at said first end is located proximate to a portion of the transmission line conductor at said second end to create a distributed capacitance therebetween.

23. The filter of Claim 22, wherein:

said distributed capacitance is located on a first side of said first resonating element; and

said first side of said first resonating element provides a majority of the coupling with said second element.

24. The filter of Claim 22, wherein:

said distributed capacitance is located on a first side of said first resonating element; and

said first side of said first resonating element is facing said second element.

25. The filter of Claim 18, wherein:

said plurality of resonating elements includes a third resonating element, different from said first and second resonating elements, that is directly coupled to said first resonating element, wherein the coupling between said first and second resonating elements is stronger than the coupling between said first and third resonating elements.

26. The filter of Claim 25, wherein:

said first resonating element includes a second side, different from said first side, that provides a majority of the coupling with said third element; and

said second side of said first resonating element is meandered to reduce coupling with said third element.

27. The filter of Claim 18, wherein:

said through transmission line is meandered to reduce the overall dimensions of said filter.

28. A planar filter for radio frequency energy, comprising:

a first resonating element having a plurality of legs and folds, wherein a first leg, a second leg, and a third leg are substantially parallel to one another, the first and second legs defining an outer boundary of the first resonating element and the third leg being located between an outer edge of the first leg and an outer edge of the second leg, wherein the first and second legs are connected by a first fold and the second and third legs by a second fold, the second fold being different from the first fold, wherein the first resonating element is asymmetrical about

a first longitudinal center axis that is substantially parallel to said first, second and third legs.

29. The planar filter of Claim 28, wherein:

said second fold is located inside said first fold.

30. The planar filter of Claim 28, wherein:

said third leg is spaced from said first leg so as to create a distributed capacitance therebetween.

31. The planar filter of Claim 28, further comprising a second resonating element spaced from and coupled to the first resonating element and having the same shape as the first resonating element, wherein the first resonating element and the second resonating element are asymmetrical about a second longitudinal center axis located midway between an outer boundary of the first resonating element and an outer boundary of the second resonating element.

32. The planar filter of Claim 28, wherein the first and second folds are located at opposing ends of the first resonating element.

33. The planar filter of Claim 28, wherein the filter has a Chebyshev-type response.

34. The planar filter of Claim 28, further comprising an input and output to the filter, the resonating element having a latitudinal center axis that is substantially parallel to the direction of flow of radio frequency energy through the filter, the input and output being located on opposing sides of the latitudinal center axis.

35. The planar filter of Claim 28, further comprising:

a fourth leg, located between the first and second legs, that is connected to said third leg by a third fold.

36. The planar filter of Claim 35, wherein:

said fourth leg is substantially parallel to said first, second, and third leg.

37. The planar filter of Claim 35, wherein:

said fourth leg is spaced from said second leg so as to create a distributed capacitance therebetween.

38. The planar filter of Claim 28, wherein:

said first leg and said third leg are part of an interdigital coupling structure.

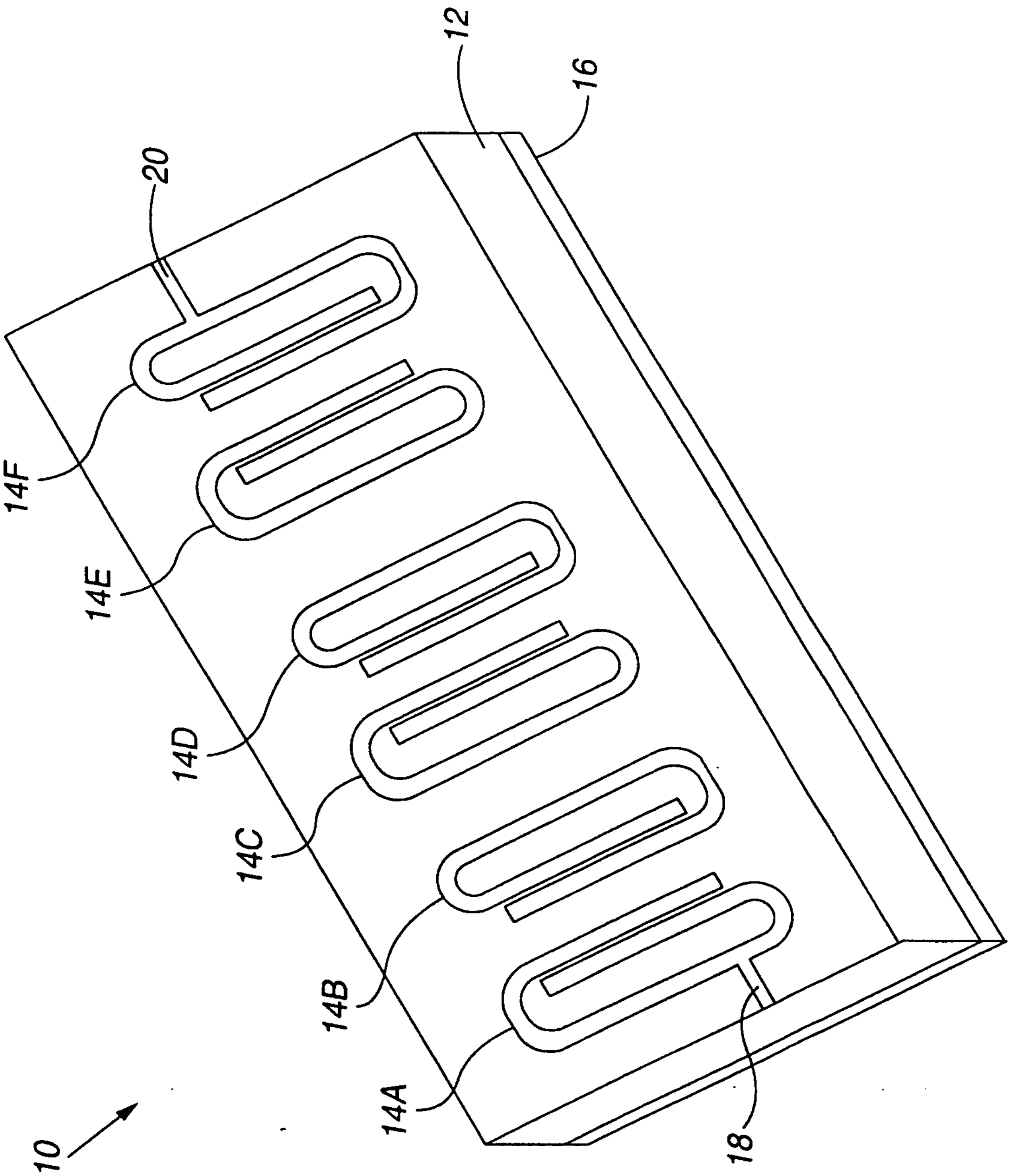
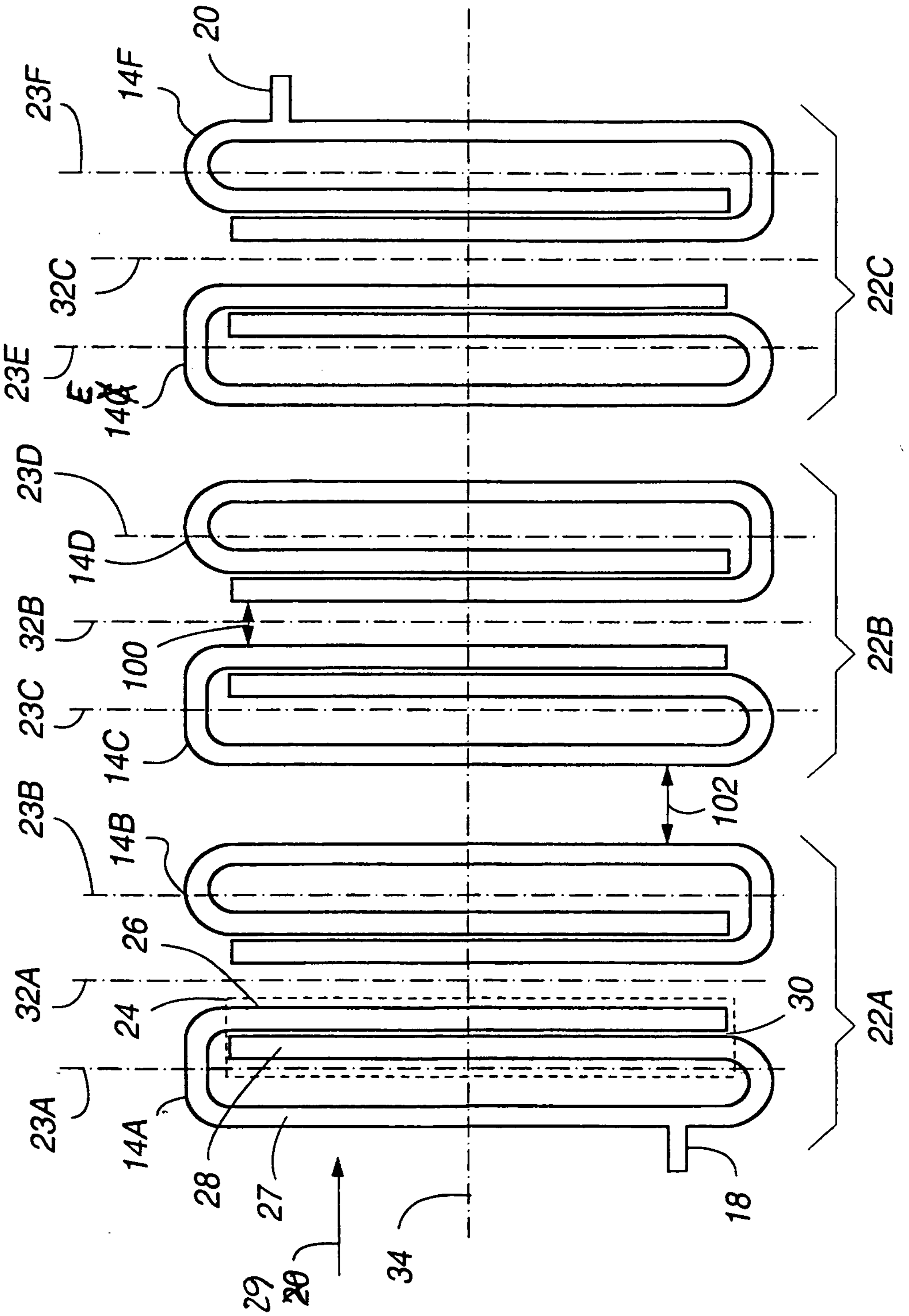


Fig. 1A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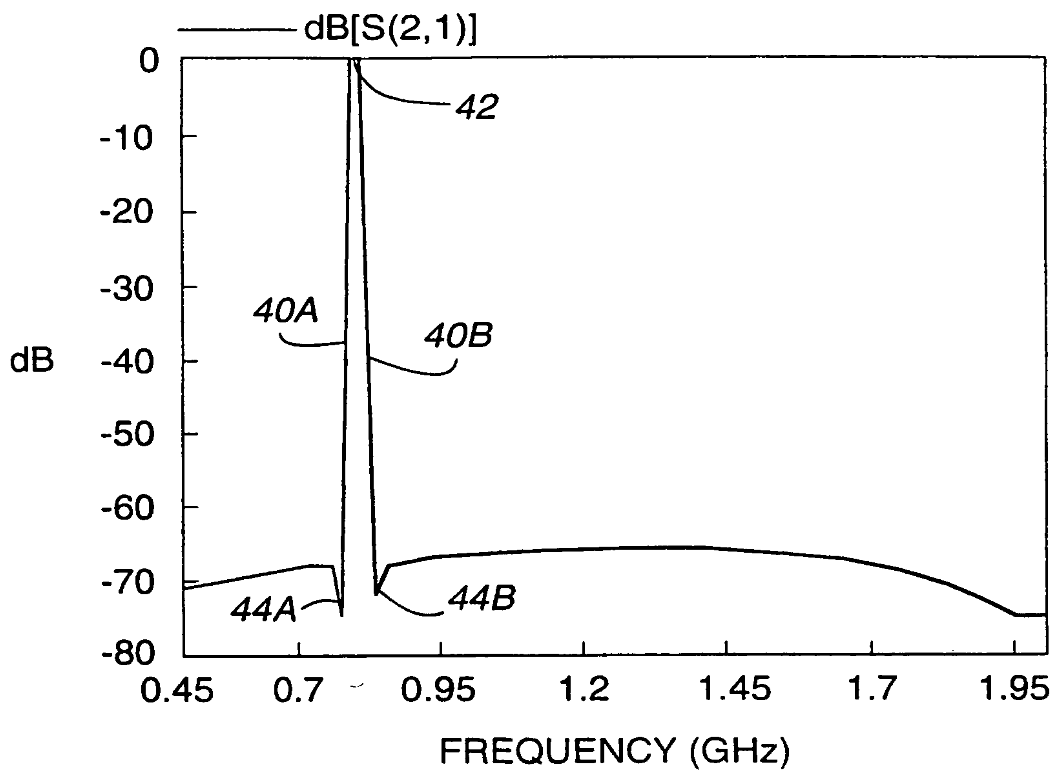
34
29

Fig. 1B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-20
-30
-40
-50
-60
-70
-80
dB
42
40A
40B
44A
44B
0.45
0.7
0.95
1.2
1.45
1.7
1.95
FREQUENCY (GHz)

Fig. 2A

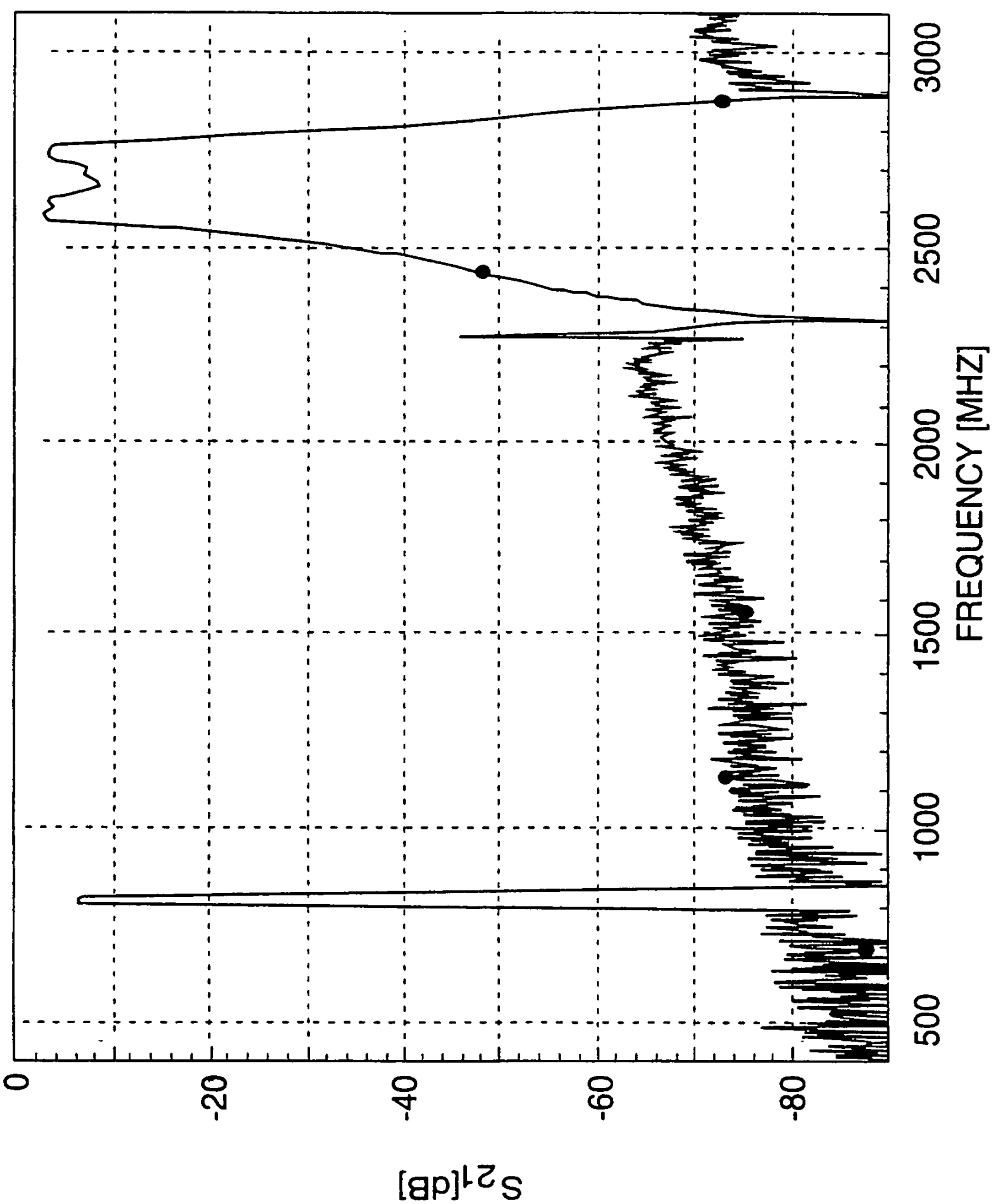


Fig. 2B

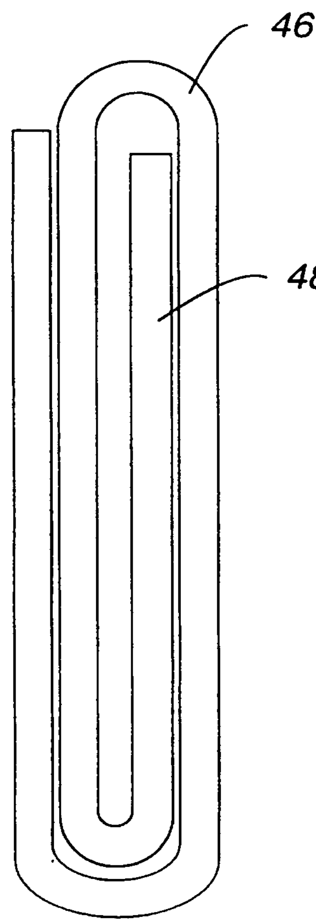


Fig. 3

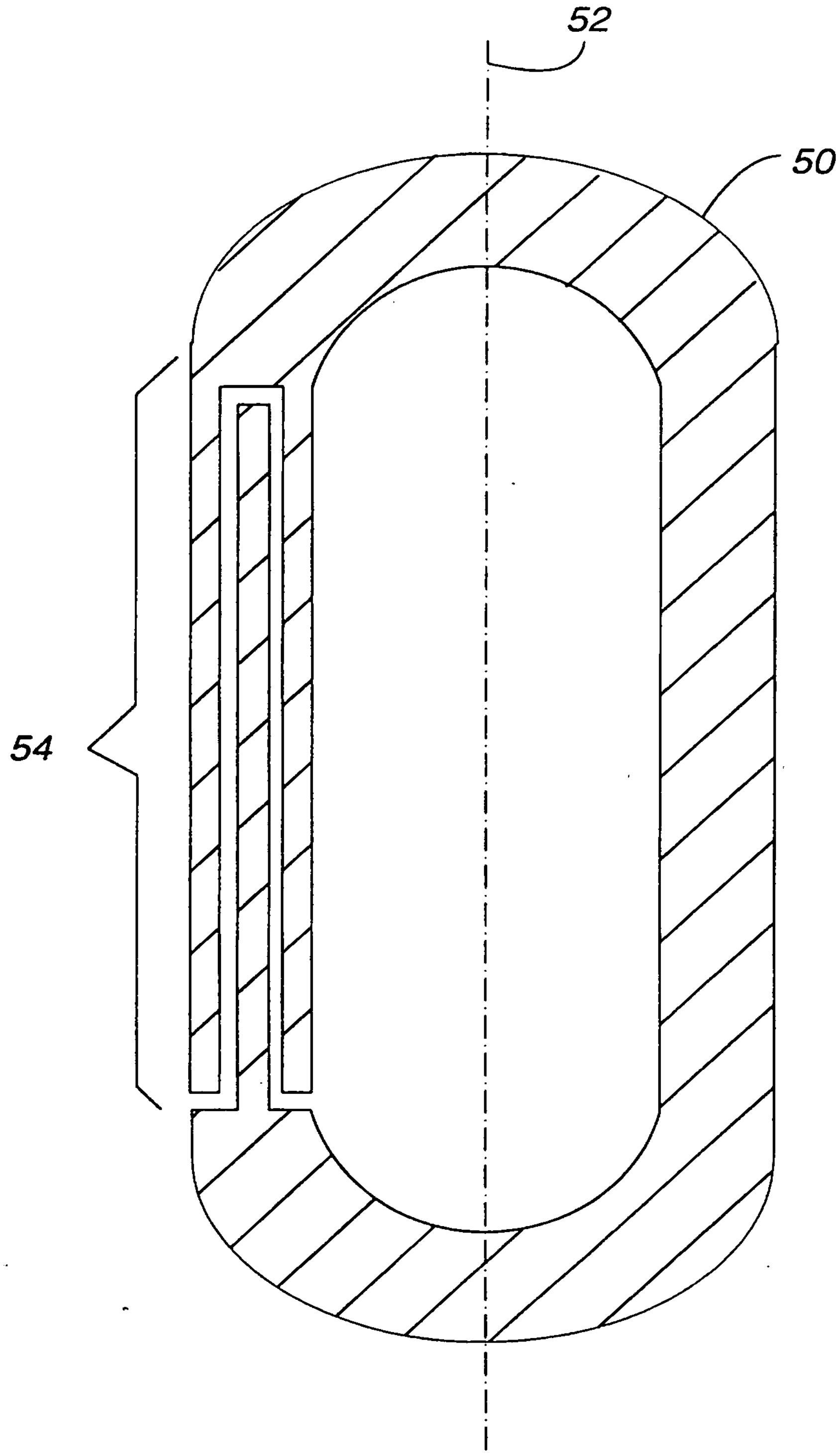


Fig. 4

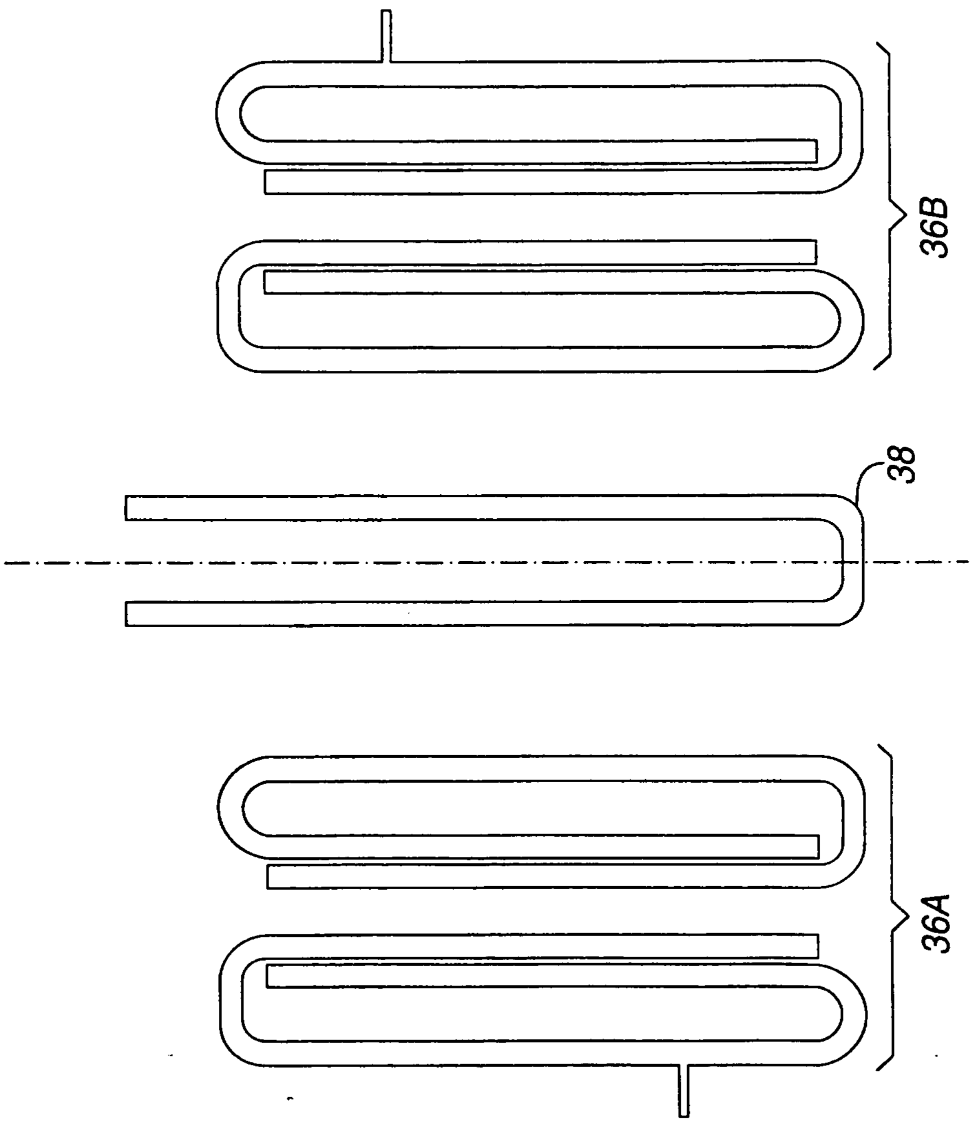
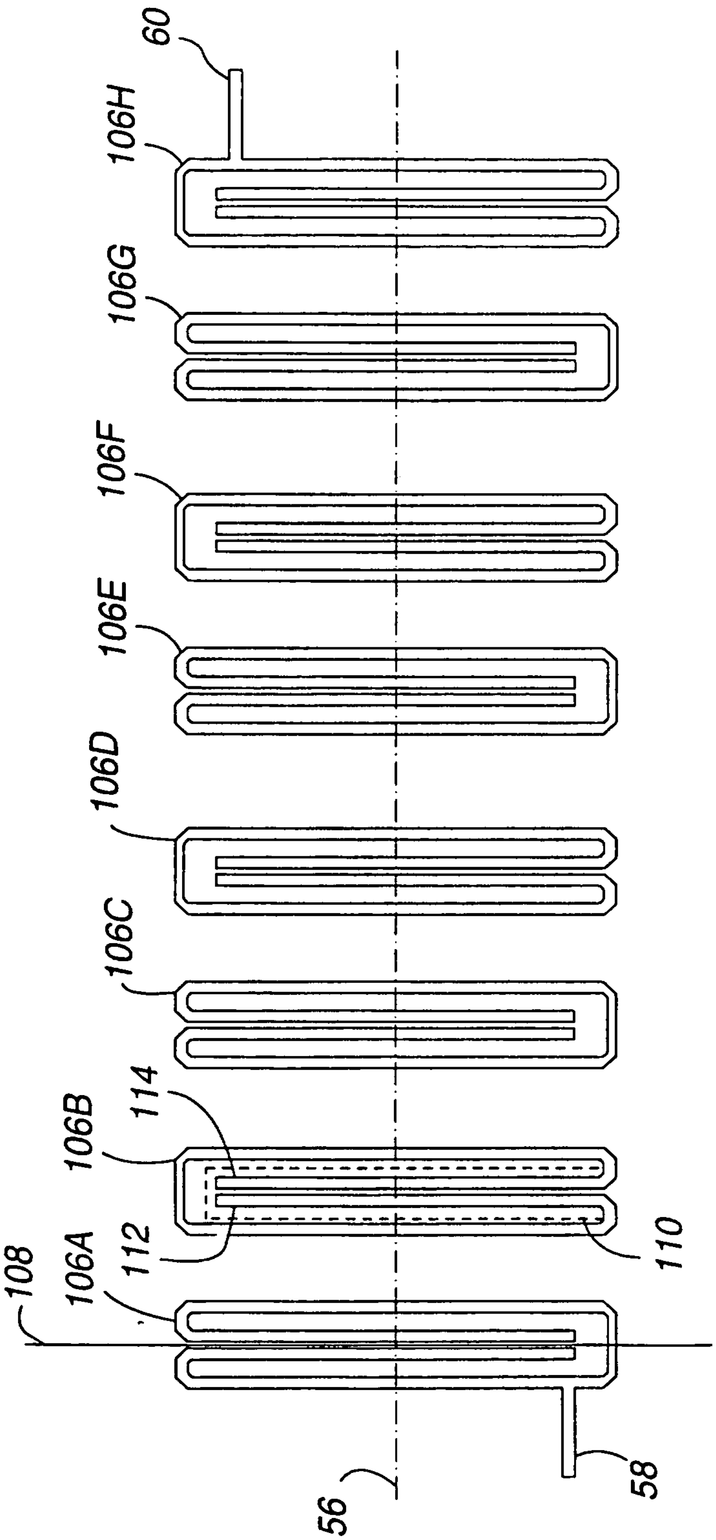


Fig. 5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106B
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56
58

Fig. 6

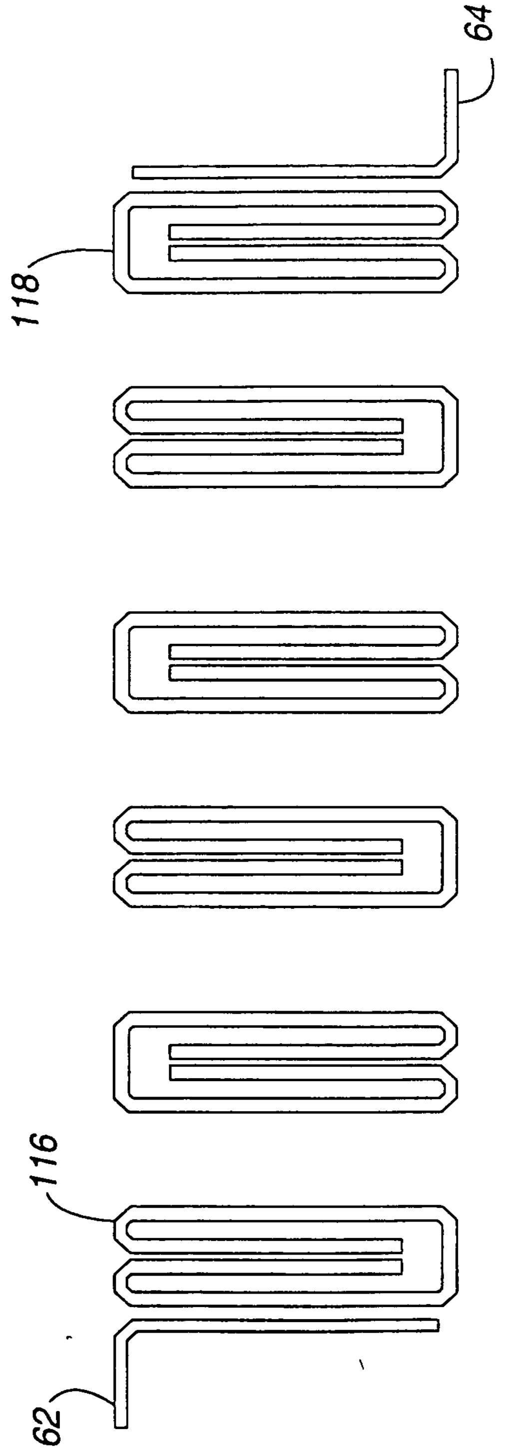

Fig. 7

10/11

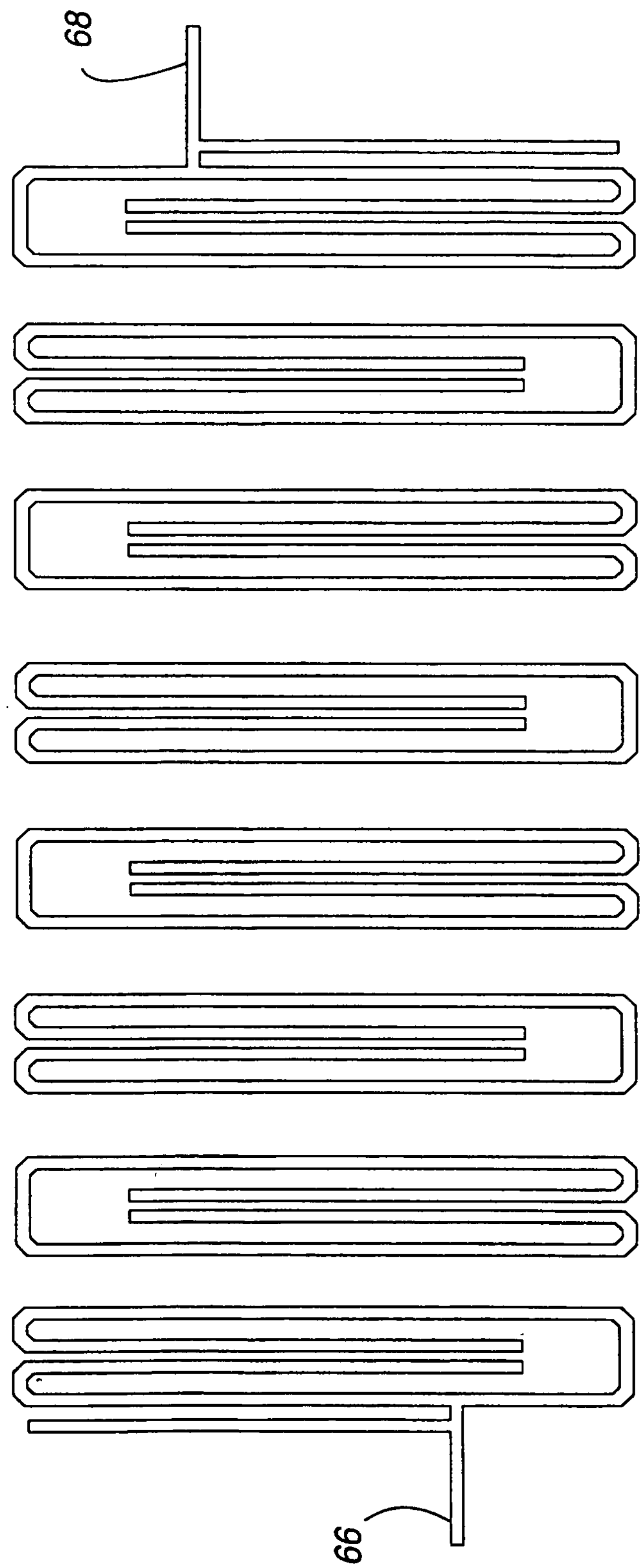

Fig. 8

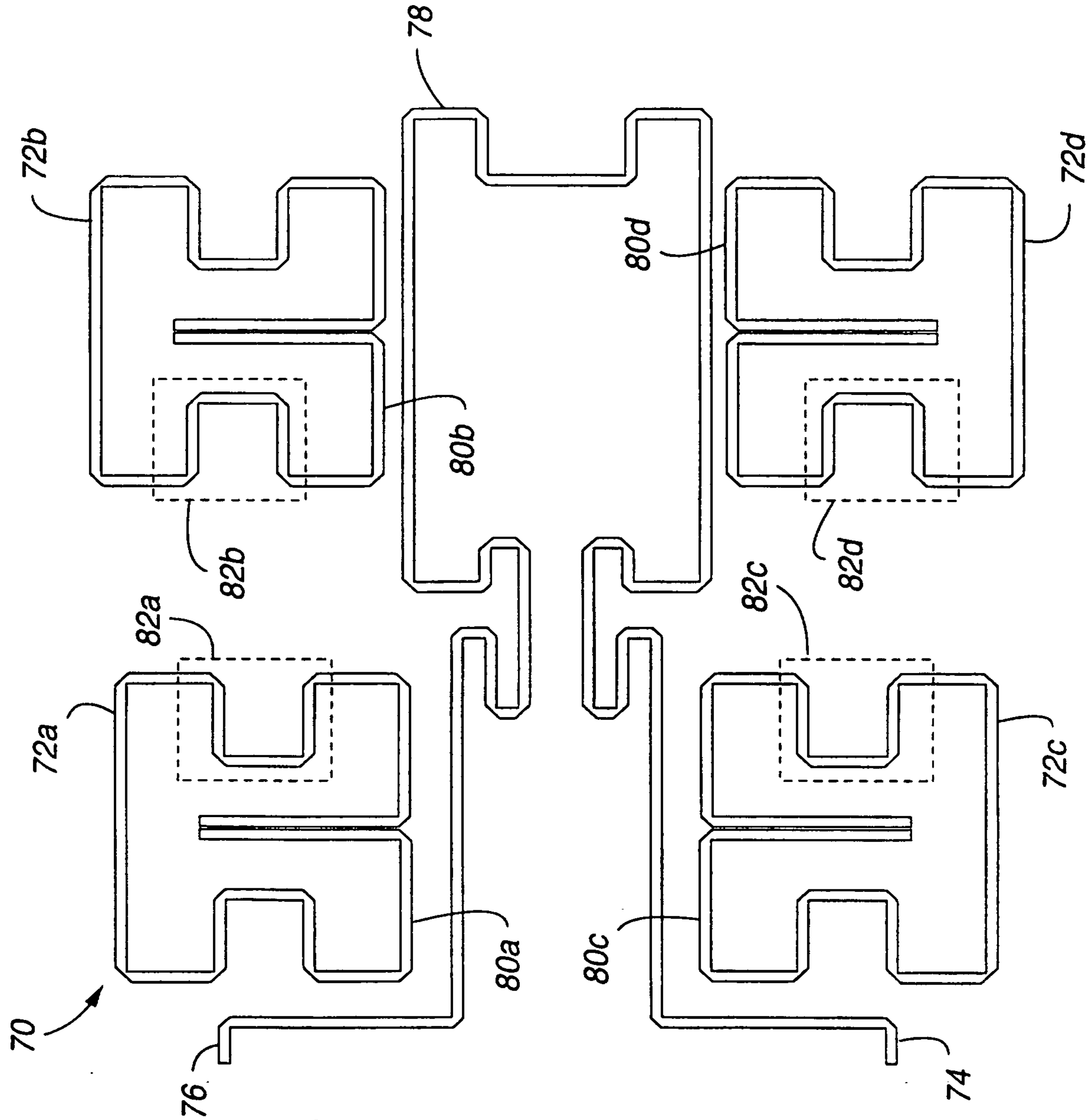

Fig. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/11172

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H01P 1/203; H01B 12/02
US CL :505/210, 701, 866; 333/204, 219, 99S
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 505/210, 700, 701, 866; 333/204, 205, 219, 99S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4,455,540 A (HENRIOT ET AL) 19 June 1984 (19/06/84), see fig. 5 & cols 3, ls 23-50.	1,2; 3,4
X	US 5,055,809 A SAGAWA ET AL 08 October 1991 (08/10/91), see figs. 9,10 & col 7, l. 6 - col 8, l. 11.	5
X	US 5,192,927 A LIN 09 March 1993 (09/03/93) see figs. 2(e) & 2(f) along with col 1, l. 60 - col 2, l. 16.	13,14,16,17
X	US 4,264,881 (DE RONDE) 28 April 1981 (28/04/81), see figs. 4e & 4g along with col 3 ls 45-50, as well as fig. 7b along with col 4, l. 44 - col 5, l. 4.	1,2; 3,4; 18-27

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
18 NOVEMBER 1997	09 DEC 1997

Name and mailing address of the ISA/US	Authorized officer
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/11172

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,512,539 (MATSUURA ET AL) 30 April 1996 (30/04/96), see figs 4-9 and description thereof.	7-12

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